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Nonlinear Geometric Material and Time-Dependent Analysis of Reinforced and Prestressed Concrete Frames

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#### **Publication Date**

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	Report to National Science Foundation NSF Grant ENG 74-02658	Y. BY	NONLINEAR GEOMETRIC, MATERIAL AND TIME DEPENDENT ANALYSIS OF REINFORCED AND PRESTRESSED CONCRETE FRAMES	STRUCTURES AND MATERIALS RESEARCH	

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BIBLIOGRAPHIC DATA 1. Report No.	
	5. Report Date
Nonlinear Geometric, Material and Time Dependent Analysis of Reinforced and Prestressed Concrete Frames	
7. Author(s) Young-Jin Kang	8. Performing Organization Rept.
9. Performing Organization Name and Address	10. Project/Task/Work Unit No.
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Berkeley, California 94720	II. Contract/Grant No. ENG 74-07658
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15. Supplementary Notes	
An exitchent numerical procedure for the material and of planar reinforced and prestressed concrete frames in cts due to load history, temperature history, creep, sh and relaxation of prestress is developed. The procedur sthod, is capable of predicting the response of these s vice load history as well as throughout elastic, inelas	nd geometric nonlinear including the time depen- shrinkage and aging of lure, based on the finite structures throughout astic and ultimate load
In addition to reinforced concrete frames, pre-tensioned, bonded and unbonded concrete frames are analyzed distinguishing thre loading; i.e., before, at and after the transfer of prestress. A series of numerical examples are presented to study the cability of the present method. The results are compared with exper the analytical results obtained by other investigators.	, post-tensioned ree distinct stages of e validity and appli- erimental results and
17. Key Words and Document Analysis. 17a. Descriptors	
Structural engineering; Reinforced concrete; Prestressed concrete; Post-tensioned; Nonlinear analysis; Material nonlinearities; Geome Creep; Shrinkage; Temperature; Load history; Cracking; 'Finite elem	ete; Pre-tensioned; Hometric nonlinearities; elements; Frames; Beams.
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## Structures and Materials Research Department of Civil Engineering Division of Structural Engineering and

Structural Mechanics

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# NONLINEAR GEOMETRIC, MATERIAL AND TIME DEPENDENT ANALYSIS OF REINFORCED AND PRESTRESSED CONCRETE FRAMES

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## Young-Jin Kang

### Faculty Investigator: A. Ģ Scordelis

## Prepared under the Sponsorship National Science Foundation Grant ENG 74-02658 0 Fi

College of Engineering Office of Research Services University of California

Berkeley, California

January 1977

Nonlinear 0 ĥh. Geometric Reinforced and ім р teria Prestressed سز and Time Concrete Dependent Frames Ana ĥ У s н. И

Doctor of Philosophy

Young-Jin Kang

**Civil** Engineering

Alex C. Scadelis Chairman of Committee

## ABSTRACT

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## ACKNOWLEDGEMENT

been Various 304 • guidance and study. Chorin gratitude very helpful. The discussions He would and encouragement author for serving rt O wishes also Professor with his ល ល like 0 1 members express throughout A.C. rt 0 colleague Dr. thank Professors Scordelis of his thesis hís the deepest course for A. X. his appreciation committee. **∀**•⊀• Kabir 0 Ha constant Lin and this have

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HOH the Foundation by Grant the University This numerical research of California, work. was Eng 74-02658. sponsored Berkeley by the The computer provided National the center Science facilities ն ct

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### INTRODUCTION

## General Remarks

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e<sup>nm</sup> ( t ) e (t) e<sup>m</sup> ( t ) e<sup>c</sup>(t) + + e<sup>s</sup>(t) e<sup>nm</sup>(t) ÷ 윤<sup>려</sup> ( ቲ ) د<sup>د</sup> (۲) (2.1)

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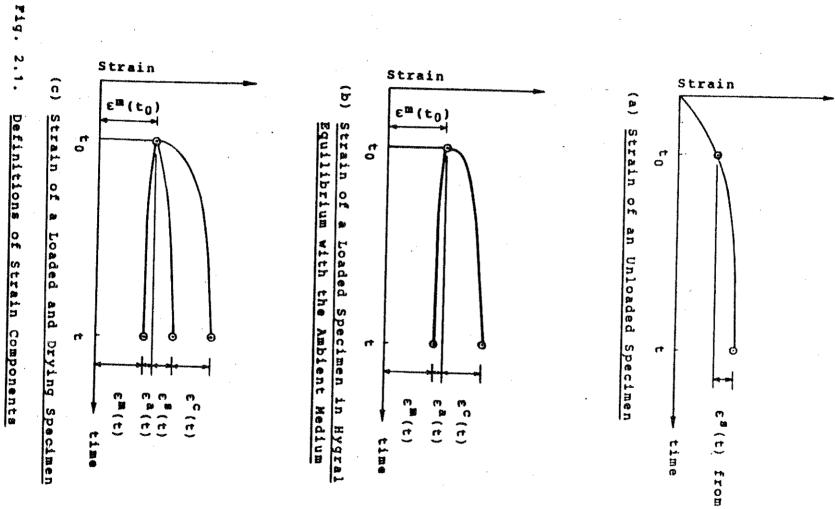
ЪУ the <u>A</u> following functional short-time μ. Ç0 the mechanical loading, strain or instantaneous 0 and 479 }--₩ stress-strain 11 12 13 14 independent relationship, strain variable caused ín.

Ĵ Ħ f(e<sup>m</sup>(t)) (2.3)

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m nt ŝ produced shrinkage mechanical where trains. Ê. a (t) Among strains, strain strain н. СЛ the these  $e^{S}(t)$ , aging e<sup>nm</sup>(t) consists and e<sup>S</sup>(t) and uniaxial strains, concrete  $e^{\mathbf{m}}(t)$ ,  $e^{\mathbf{C}}(t)$ , strain et(t) 0 stress e<sup>a</sup> ( t ) creep are non-stress strain e<sup>c</sup> E<sup>a</sup>(t) are and thermal рі († time r† • (ft), ά roduced strain Non-

ъ strain rt roduced by rated in The 0 m meaning an ₽ig. temperature unloaded 2.1 Q H (53) except each concrete changes. 0 H these specimen. на 0 Н ₽ig. strain the 2.1. thermal components Shrinkage μ shows shrinkage strain 0 H н. ω which con illus-}---08



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the e X 0 time aging enon modulus ju. et. that This sustained hygral N • en n Â. (A) н е cept н. Ю . . . tly and external đ mechanical Ð <del>ہ</del>. о. т the increase increased strain. 0 F shows ⊮. 0 equilibrium with the drying thermal 0 h called mechanical strain impose defined axial This concrete increase 0 H the in strain under specimen Fig. ٨q strain strain the aging )... 10 internal, ρ, strain history compression. 0) () stresses e<sup>c</sup>(t) caused 2.1.0 the due a 1 8 in which all volume compared of concrete, and н. Ч Уq present. shows с† О and at time 1 5 6 ambient defined the () () a sustained stress, X P 0 Ha 0 Ha change which Ha C t 1 2 6 time aging to the strain note temperature ά **f**† strain 03 03 the medium, concrete elapses. that is smaller that 0 creep. strain the the concrete history the subjected OCCUIS specimen changes decrease strength ) (a rt components E O This strain than that at whether it also time 0 5 independphenom-٠ ő ц 11 called ц. Ц β. н. П т 0. and note カリート・ loadg. tine

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The ing the S z ct ο time have domain is , 00 ŕή ions н М which n results E L O H Ø the alculation Ç# FD 0 n D Then finite iπ Ö this study, the total these intervals may ÷ divided into ц ц Q, obtained step n o t f i rat number <u>н</u>. number o f 0 0 , D G forward H concret time н 0 Ч 0 formed н 0 М 0 0 a discrete number of the time step, each time a 1 0 integration ው same ()) ()) time dependent strains steps called time п† 0 time step steps considered followe length arrive 5 and 60 լ... ն -5 þ ው rt successively, Ŵ performed by steps. rt H N time. the analysis, æ 1,2, intervals each w ŝ æ Ŵ 1 n final . The ው (ተ . Thus t ne ·,N, where <u>ي</u> the solution. junc E O starttypical adding analytime

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(A) time adding tep ťn-1. interval (1) the Total increment t 2 - 1 strain ő 0 15 ដ ო -5 total ው ct r† 0 the time strain total step Δe יי ב strain Ħ occurring р. Ø obtained е n-1 рі с† during time ЪУ

ສິ N ຍ ສະ1 + Δε<sub>n</sub> (2.4)

changes. ring contributions between (2) The time đue increment 0 0 steps creep, tn-1 0 non-mechanical shrinkage, and rt B ր։ Տ aging obtained strain and by ∆enm n temperature adding occur-

∆enm ∆e<sup>c</sup>n + ∆cn a 4 ∆en n ÷ Δent (2.5)

obtained ٨q Non-mechanical adding the increment strain ы С П ∆enm рі rt († 0 time the step previous -ສ່ μ. W total. then

€ มพ N . ຍັນສຸ +  $\Delta \varepsilon_n^{nm}$ (2.6)

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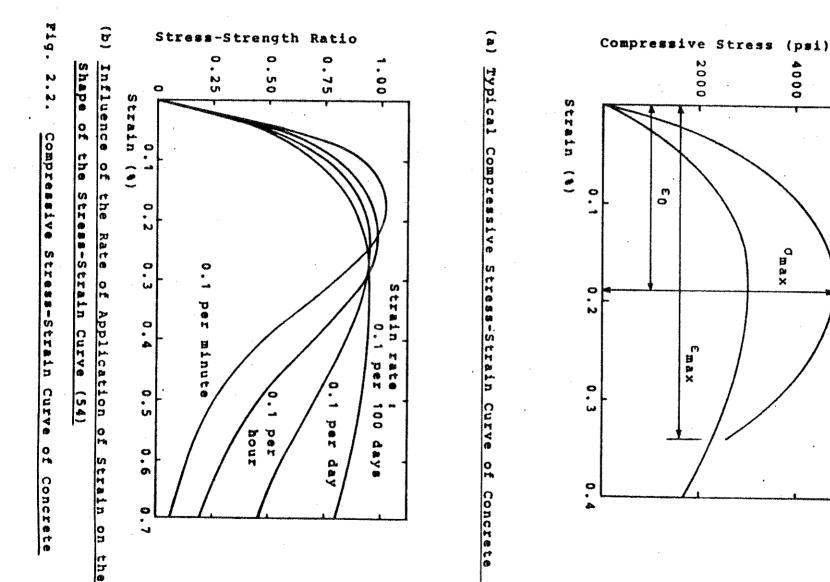
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**.**... βu ហ († ma sion Э p. rh, 5 ide Ø rt late H Ø Ô. ŵ ГY о а â ō moderate rt н н S н • n n 14 17 μ. ير. سو which having э t Q s O н 0 7 beams. n 50 ի--տ appropriate that the н. rt testing speeds rt subjected. two . ₩. († 15 ۲. stress-strain S Fig. Such different made, compressive N + n b rt N н curve and ain . ք Concrete 01 the compressive shows measurements relationship can an axially stres type t w o 0 լ.... նն S of stress obtained used -strain such curve strengths loaded о п 0 Ha mostly the CUIV the by ст 0 (N in 1 concrete ٣ Ō compression cylinder mate which (53). obtained **H**•• ٥, compres--۲۹ ۱۰۰ o ħ ω the щ. pricy1-

σ Ω m finally Ъ which reaching æ ercent urve max. Ō ملو rtional, ω ŧn 0.44 The has јч. СА The 0 show portion zero slope called the curves 1 1 1 1 1 1 1 the initial linearly elastic followed ¢, value maximum descending branch, reaching in which consist initial 0 and maximum stress А р atress. approximately <u>p</u> 0 Fi curve stress an modulus initial relatively with The and 0 part initial <u>p</u> strain 0.002 decreasing <sup>o</sup>max concrete extends the in. are ው ናተ slope рек μ maximum strain closely strain († 0 slope straight 0 Fr in., about the proе0 and ယ ဝ

S 0 maximum strain, 1.1 strength lowe note 0 rt ÷, H D н Ф å 170 rt. (A н higher ¢ (A ц Ц The ÷ strength. μ. Ω CUIVE 01 (0 Fig. р. СО largely shape strength shown 1633 )---10 2.2. 0 m than a 1 s o 5 determined brittle H t p, the that ۍ ان Fig. µ. Ø FOR affected compressive stress-strain curve also larger the • N • high-strength р. Ф N 1 seen рÀ initial ٠ Уq than fracture ju. ct Qi (54) that the that compressive modulus н concrete p concrete r† Ø occurs 0 14 0 concrete 0 Ha application рі († 0 M strength. concrete The p, lover larger havin shape 0 m hav-0 ģ 000-Σ P

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(53)

with magnitude analyze concrete structures for long-time loading more consider siderable strength-time curve is shown r n t o ц С 1 1 often mentioned. 410, ω jected to n 0 0 0 ĵ, train oncrete specimens such as cylinders, cubes and prisms, subtely. the United influenced the maximum × 5120 consideration in design practice. time 12 in. cylinder, denoted by  $f_c^t$ , is most commonly used relationship of concrete is largely determined by the this variation in strength with time in order 0 of its compressive strength, it is . C8 gain in strength can be noted. uniaxial well aggragate and gain of strength with time are ЪУ States, average stress obtained from the many factors, among which water-cement known, but The increase in the strength of concrete compression. strength The compressive strength of concrete 1. D н. М Fig. is not often fully The ν. ω compressive A typical compressive (55), Since the stressessential usually in which contesting strength taken defined 9006-0 đ H A H H H 0 O Ha

quation (f') t = for predicting compressive strength at 04 + D + C + C (fr) 28d any time. (2.9)

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used n average where, Hh, asting ¢, and for  $(f_c^{l})_{28d}$  is 28-day strength, t of concrete, values the particular b depend on the type of cement determined from and concrete. a and some Б are constants. Following 8 8 μ. ທ test and curing method time specimens ۲. ۲ approximate days The values after 976 976

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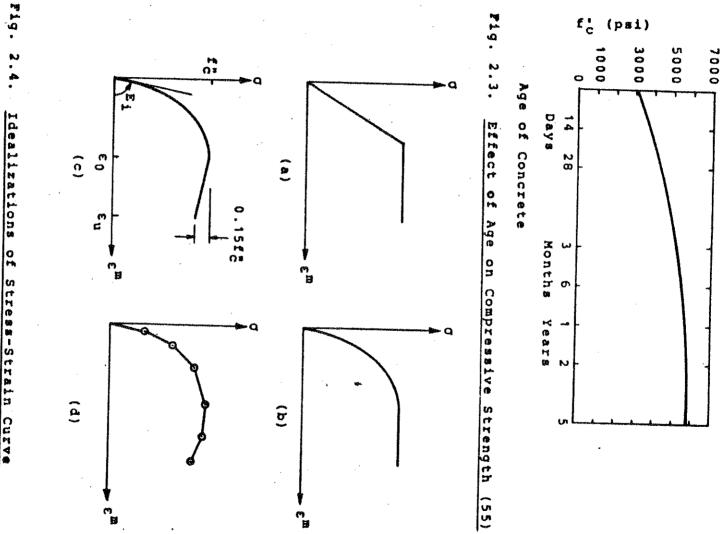
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Stress-Strain Curve

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the mathematical formula for formulas oncrete Fig. frequently utilized mathematical ≯ s S S Moist Moist team te an 2.4 Ċ) developed are summarized ы. Ю basis cured cured cured cured <u>þ</u>i convenient for the concrete, concrete, concrete, concrate; analysis the and type tуре type type stress-strain relationship of necessary tool. I I I TTT ы I cement 0 Уq cement concrete cement cement idealizations Popovics •• \*\* a=1.00, b=0.95 a=4.00, .... 49 a=2.30, structures, a=0.70, (58). Many 8 7 8 b=0.85 empirical Some of b=0.98 b=0.92shown ρ

¥ 2 3 ta model. labs used by Fig. and This is 2.4.a shells. レビコ the Shows (31) simplest in his study <u>p</u>r linearly of nonlinear elastic-perfectly of reinforced concrete models. plastic This model

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0 proposed ħ **9**# parabola and a horizontal line. 19 by the 2.4.b European Concrete Committee shows аn inelastic-perfectly (59), plastic consisting model

rt rt Ø 0 ng most curve 50 ы. tress-strain curves, tudies ranklin cular special versatile 19 . 6 t 0 Hh concrete used (12) and Aldstedt approximated by 2.4.d reinforced 02363 model capable of shows 1. 1 which **N** the use of concrete φ piecewise **بر**ز available (47) used this model in their the series experimental frames. representing this model is restricted 0 linear straight line Although mode 1 data wide variety in which for this segments. the ₩-the 4 7 9 4 7 par-0 11 0

≻ mode 1 which represents t T e stressstrain curve 0 H

modi the wide their concrete vestigators gested by Hognestad present fications. variety studies columns, investigation ; Kroenke, et 0 Fi 0 This model has concretes prestressed Wilhelm, (60), al (61) in their this and י<del>ין</del> ה (D) (T) concrete D# is shown а 1 been mode 1 mathematical (52) widely used is utilized columns, and Aroni in Fig. 2.4.c. study formula đ ٨q (63,64) 0 Hi with name many slender ¥as minor <u>p</u> FOF ц. Э н. Э - ចំពន F e K

gua tion The ascending part 0 14 e t h e curve ₽. 01 described ъy the

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$$J = f_{C}^{n} \frac{\varepsilon_{m}}{\varepsilon_{0}} \left(2 - \frac{\varepsilon_{m}}{\varepsilon_{0}}\right)$$

(2.10)

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$$\varepsilon_0 = \frac{2f^*}{E_1}$$
(2.11)

Eq.(2.10), where [1] #\*\* н. 09 the the tangent initial modulus, tangent tri Th modulus. ы. Ю obtained. Вy <u>с</u>, H fere ŋ (\* |ω rt ing

$$E_{t} = \frac{d\sigma}{d\epsilon^{m}} = E_{1}\left(1 - \frac{\epsilon^{m}}{\epsilon_{0}}\right)$$
(2.12)

trj rt the the Obse 1100 secant ascending rving initial the modulus tangent branch three በ) rt equations of the the modulus peak point stress-strain curve is ы Н. given has above, \*\* twice the € Ø the tangent modulus note magnitude a parabola that •• 0 14

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(2.14)

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Long-Time

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(31) tension reinforcing steel קי Tension their stiffening stiffening studies is neglected V a s of reinforced incorporated 0 concrete in this Уđ concrete slabs after Scanlon study. cracking (48) The and shells due effect and t1 0 111 0

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ten tri r† O weight jui. Ծ Թ ()) ()) Then The constant, and the follows. slope pcť, the tensile of the parameter stress-strain tensile stress-strain same . N 17 ឯឧទ 90 69 the value 8 1 1 relationship initial о њ tangent Curve 0 . 6 027 ct O is assumed modulus e D

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1 and prac incorporate hei Η aging 0 1 1 1 service <u>نم</u> ŗ Ľ conditions the the study lives. time dependent 0 0 M service. concrete effects Thus structures 0 H н. rt ₽. (3 creep, important throughout shrinkage ц О

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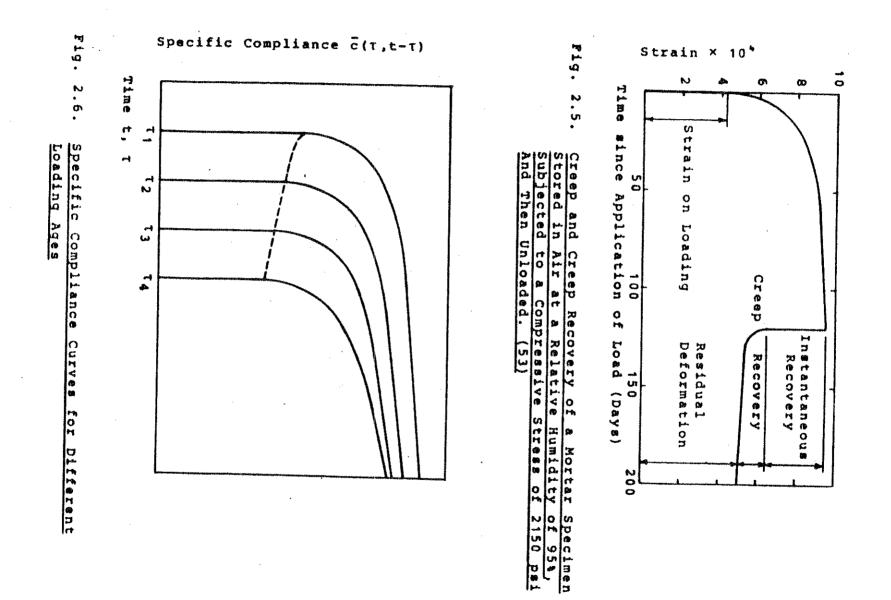
ЪУ **n** the н shape that mediately When rt Ö nature load application of the loading tained reep apidly <u>p</u>i creep initial loading. age, which is smaller than the instantaneous the gradual of the curve, streps; 0 H 0 ps ct sustained load strain becomes by creep any ĝø 1 1 1 1 1 1 creep recovery curve is similar to that of an decrease decreasing other amount ----0 whether the load illustrated in Fig. cause recovery in strain, called creep This instantaneous equal to the is removed the strain more than twice the strain increases with rate. such stress reaches the At 0 8 ۳. ۵ 120 temperature instantaneous strain ېد tt produced N.5 days e n a recovery maximum (53). strain after decreases recovery. by external changes. value р. (A strain sustained time due After on loading followed t he 181 more the ри ct a rt The The

water theory FOR FOR S tood. example, The theory (67), And mechanism there viscous mechanical (69). are 0 Ph flow theory (68), many creep deformation theory theories is still attempting 300 and completely (66), plastic seepage to explain 0 undergel н. т

Some 0 H There are the important many fact factors Ors influencing are discussed ore Ø below Ъ. O Ma conc H O C† ID

(1) Age at loading

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ing Ø ve modulus ₹e gene F a g and rt defined ٢ħ 0 train :5 ወ lopment ŵ ß p. 5 de d Ŵ also rt, can rally O Ħ the et after reep, 1 and Q age b e 0 Hi note с С 1 FJ H n 0 smaller ρ Ø ģ reep the h instantaneous ø due attributed t n e ٠ later lasticity α rt strength that N . თ same time 0 strain total loading typical age the than ω unit stress-produced 0 ť with н. Ю 0 instantaneous strain that 0 r 0 Ηh the spec strain with concrete. smaller interval the sustained time. shown o Fi degree specimen ۳. m the μ. + n due This following compliance stress. specimen Speci of hydration п 0 increasing strain, loaded decrease the . Fr 14 C of the specimen initial inc loaded ∑ @ compliance instantaneous curves Ω rt Ħ H D age 3 010 late and 9 S 6 ው በተ creep 0# († н 0 н loading н first the in the age earlie loadμ. р Ч (A) ը Թ թ. տ m T н

(2) Intensity of stress

ហ σ يسو مەر 7 Ó study. Above н function failure about rt 2 3 **e** Q нħ ange 0 h near 0 0 0 0 (A 61 developed J T つ 約 Ω о . 05 0 Hi ω Tee intensity, Ô H n H 0 00 4 reap stress-strength 0 the working ΰ, |--. (0) ő (0) }--account time. time and 0.6 assumption formulation shown proportional to the applied a n . stress. t he empirical creep This 10 H ц. Ц stress-strength Fig. ወ this dependency ffective ratio increases that used At 2.7 nonlinear formula evaluating higher deero 5 1 1 0 (54). stress the 0. 8 0 Hi рі ct strain stresspresent ratio ő an creep creep Manuel concept 0.9, increasing ր. տ stress 0n based ia († effect and proportional study, creep rength 4 1 1 0 explained creep 01 McG within intensity in the produces rate which н Rusch' ratios, 0) 83 Ø G D F the pa а њ ր. ն 0 (A)

chapter 3 is used

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(3) Aggregate content

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(4) Compressive strength

88 († causes the decrease stress, creep N (A) ingth For 0 0 constant concrete թ. 0 generally in creep as shown cement (53). inversely paste Gain 0 Ha content strength with proportional in Fig. and D t b e 2.6. 5 a m e time also ő the applied

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50 10 creep is several weeks specimen, but furthur Creep the effect decreases with an increase きを出っ after the application when regardless is apparent. the specimen 0 the thickness exceeds ₩ # н. М size of the specimen of the load, ц Ц also.noted the size the that about 3 0 Ha H B t B the beyond (75). 0 Ha ኩ ተ

prior みたぶ en t 40 relative Creep с<del>†</del> О humidity loading generally decreases humidity. if concrete B c t has creep is not reached hygral with 8 3 increase affected equilibrium 1 1 A A the the ambirel-

(6)

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ranging 80 deg. Creep from ng generally increases t b e 0 deg. rate F to 0 17h Greep 180 deg. decreases proportionally 'nj (76,77). ч Р r† 0 about 11 0 But temperature beyond 300 00 deg

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the Base Committee (Ť р. 0 ò F σ (A prediction р, redict Ph, ъ on hundreds actors rediction 209 the influencing (56) 0 H ore 0 14 0 Hi creep. 0 suggests creep experiments 0 14 conc н N creep, following a difficult rete and Åq ա. ល many investigators any ponug form formula task rt 0 0 /ħ 0 0 because equation attempting approximate 0 , ACI h н 0 1 Var ٠

Ô 1 1 1 10 t-T) 0.6 + (t-T) 0.6 с ц 2.18)

906 Hi jui from tial ratio where loading creep cient 0 the strain •• 0 strain Ct-1 concrete in days с ц --creep casting с Д ⊮. ທ ρι rt بر ۵ а t ₩. (0) computed strain at infinite time after the loading (t-T) days the ultimate 0 11 creep coefficient concrete 0 0 ն Մ rt follows }---60 after loading. measured creep the loading current coefficient The defined i n days ultimate ő observation initial loading 2 8 --define and the creep н strain ratio to ini-Ω time is the as the coef-0 ри ct

ິດ whe thickness due 1ess these slump, H P rt 0. N С с slump, ų, × . ω 5 creep loading percent \* o f ж Ж for 40 correction member × Ho t ne percent fines age, humidity, minimum thickness ς α Χ following standard conditions ማ and in. ጽ ካበ factors ambient S S X 8 1 F and 0 H א א 2 less, content × ≥∩ have relative are loading the сгеер respectively. value humidity, correction age of unity, 4 0 days --minimum member, 4 in. All of factors Ħ 0 . • 01

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weight, t)) humidity where ч. 8 the H and )나. (22 a lump ц. П the percent, ≫ ) () 1 1 loading the inches, 1 - B н age is the content hţ ц т i S minimum days, the 1. D percent percent H thickness рл. Ю t he 0 ambient fine ц. Ц aggre inches relat g a t e 1Ve ъy

1 5 D C 05 erally 0 ymptotically 8000 thermal 5 9 drying n decreases member rete ц ц Shrinkage increases with Fig. produced ы. Ю and b u e' generally 2.1.a with volume with time ambient 0 time concrete ŝ. the shrinkage changes considered the dependent relative increase similarly increase ы. СЮ 0 5 defined reaches 0 F humidity. carbonation. volume r† 0 rt 0 aggregate 0 arise creep. ₩-11 13 wate (# (R change. non-s maximum from H. . cement volume Shrinkage Shrinkage \*\*\*\*\* 1055 } \$ value • ratio can 0 8 N C 512e wate 0 14 0 gen-64 (5) (1) ກດກ 0 H .

rt լտ. 09 ซ H C ferable 40 have experiment 98 |---4 shrinkage 8 rt H ¢, . 9 1

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rt where 0119 due KH, KT, đ humidity, Ka Ka <del>بر</del> ان ات minimum and K<sup>S</sup> are shrinkage thickness 0 member, correction slump fac

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с Си HOF steam cured concrete X 、 17 80 × سم Ka Ka × ≫ø

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ري م N 008 ħ 0 × 10-6 moist × 10-6 cured X X 4 次. 日間 concrete يخ دە دە 27 8 0 ズ うち × Þø (2.23)

The ultimate shrinkage coefficient ອ ສີ ສີ computed 04 69 follows.

Hh ŀħ . ա տ ហ ហ 3 to **%**e ť # .7 Ha 0 H for moist steam cured cured concrete concrete (2.22) the ing. of curing, and where, crete, after infinite time, t is time in days after casting of conthe completion of curing, Committee. The 6 t - t 0 т О following values of f and  $t_0$  are recommended by is the age of concrete in days at is the shrinkage strain after m μ. 0 a constant depending on the ຕ ເຊຍ is the ultimate shrinkage strain (t-t<sub>0</sub>) days the type completion of curfrom

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11 A11 ness from slump, 40 unity n no n 6 8 ø 0 ង ។ the 0 factors Ηh for the content, percent membe standard percent ambient the ŝ 0 T 0 shrinkage Н following standard conditions used in. conditions, 0 correction less. fines relative the and For following а 12. Қ factors have humidity, conditions content shrinkage \*\* minimum 4 in. or less which differ respe t ne value ctively. thickcorrec-0

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5 loading tained crete. the Aging stress H H mechanical would strain of concrete þ concrete 0) († 0 0 time the strain 5 a me °, prism is subjected to with time due to the 9.5 the strain can be defined strain Da Fit 9) († some the o<sup>rt</sup> 9 time as the constant sus aging 1-1-**E** c† exclude 0 f 8 F t 6 decre con-Ω N I. æ

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(DJ G due rent strain the creep **n** 11 C C S S any mechanical 0 11 stress and the time, n N would 9 shrinkage increase Ωı Vi correction factor **(**) rather ġ, strain reduced. function than actual physical straining. in the modulus of strains, р rt time 0 Thus the current ង ន 110 H t) ¥e corresponding shown the C a n concrete with time, ן. ד calculation consider mechanical Fig. 1† 0 2.1.0 the the 0 15 aging strain the constant But cur-

рі ст steps σ<sub>n-1</sub>, The tn-1 and can increment 0 D t<sub>n</sub>, assuming calculated 0 aging as follows. strain  $\Delta \varepsilon_n^a$ that 1 1 1 8 stress occurring remains between constant time

Δen N g<sub>n-1</sub> (a<sub>n-1</sub>) gn(a<sup>n-1</sup>) (2.25)

Lows time defined where, .cal steps. strain q 1 n ы. Ю Eq. 11 94 Explicitly, time dependent terms (2.3), 0 fi and stress,i.e. function g can be subscripts function for computing an (n-1) inverse and expressed Ħ function represent mechanр С 0 10 H H

ខ្លួ ещ 2 a∕Ei t) <sup>0</sup>3 5 ŧ v1-a/f") tension 11 compression (2.27) (2.26)

where, 0 and currently valid values t-h 0= have с† О e D used. o F time dependent variables 년 문 -

2.4 De formation Due с<del>т</del> 0 Temperature Changes

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cooling. ronmental during Concrete their conditions, Stresses service structures induced lives not рпq ф are also Å, subjected temperature о Ц Ц е only с† 0 due artificial rt 0 ф 0 temperature changes changes heating н 5 ļ'n statie envichanges о F

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and Ψ cally erature damaging Uniaxial thermal indeterminate changes has to the structures. concrete rt 0 strain, 0 D incorporated structures m rt may Therefore 0 0 expressed are i n the the often effect analysis. as follows. substantial 0 Fr tes-

ო rt T 7 a (T) dT To (2.28)

U B **ور** دسو دسو 82), concrete and follows. ature cient where temperature dependent. a(T) is the coefficient temperature and To change. 0 m i x the magnitude depends on the composition of thermal expansion н. Ю reference and its hygral state at the time For this levels. temperature, study Then of concrete is almost But of thermal expansion which may Eq. (2.28) Q is assumed to below 600 <u>ا</u> μ. Ω current deg. can 0 U <del>ار</del> اربا 0 0 0 F rewritten temperature constant the temperthe constant tbe coeffi-9¥ r† ~ ល ហ

m . m  $\alpha(T-T_0) =$ αΔΤ (2.29)

15 1.5 83 chapter the discussed previously. Creep present س • strain investigation, and will be of concrete The effect is taken into is influenced discussed አ temperature account in detail

່ ເບັ Load Reversal and Complete Stress-Strain Curve

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model ture loading load or wind load are not considered in this study. But unhistory The of the and effects of dynamic reloading stress-strain are accounted due 0 curve. for by cyclic loading such live 9 load history Even simple under load ρ and temperaas seismic reversal constant SUS-

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H rt н ained ame s d u e load rt O unloading could creep and shrinkage of concrete. take place 1 n reinforced concrete

for Ph. μ'n lexure. hŋ 1 D T. thei (1)The 2.8. ĥţ. load The The study of prestressed concrete slope following Blakeley reversal 0 the and Park model assumptions load reversal utilized (83) utilized are i n sections made path this н. Э ľ n 9 study is this similar with cyclic 10 10 10 10 model. stressshown model

when the (2) tensile Tensile stress exceeds its maximum failure or cracking 0 H concrete occurs tensile stress אי רד יי י

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when deoo ressive strain the (3) compressive mechanical strain exceeds Compressive е. failure 0 crushing 0 H concrete јч. rt 10 max1mum occurs

any sumed closing **sile** resistance 8 t r e s s (4) с† 0 of the close Once again. orack i n concrete compression and reopen But and |---ft н. 10 reloading. can take cracked, ₩~ [† compressive stress Thus cannot in tension the crack take any ۱. ۱. without a 8 tennodn

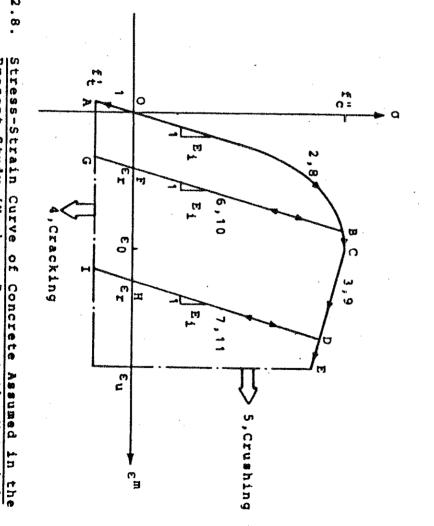
រកខ responding to concrete strain mary (A concrete , 11 (0) tates, ы С compressive loading, 11 11 curve the computer as shown in Fig. material material In the and the unloading following description mechanical evaluating the maximum compressive states, state program developed and reloading н. И 2.8, for the concrete classified into strain stress exceeds н-Ю stress, of the paths purpose defined and н 0 Н ۴ 0 ع the ---à ---à this study ĻIJ -**a** -# нь 0= са Са Са the of tracing pridifferent the tangent different yielded 01 stresstrain the moduwhen Ω Ö H I

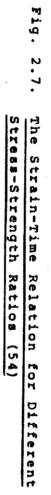
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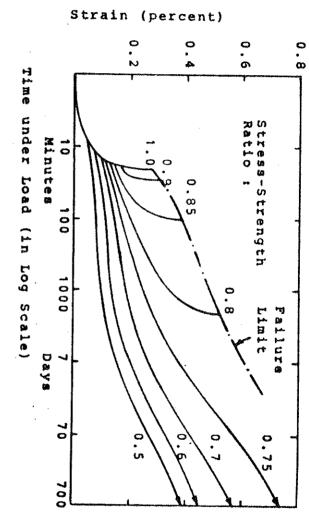
N ٠ Stress-Strain ( Present Study State of Concre Concrete) Curve Curve of Concrete (Numbers Represent the Material Assumed 1 1

Fig

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Ч 0 ł۳j FOR 1 n 0 H М this study can now (A states またみたき q a tates Q The (11) (10) (9) (8) (7) (6) (5) **(4)** 3 (2) (1) . 8 Eiem ŧ н О = complete . \_\_\_\_\_ ò Γn In HB Πn (path CE (path OC Crushed Cracked H In H D ω ຸ  $\frac{\varepsilon_{0}}{\varepsilon_{0}}\left(2-\frac{\varepsilon_{m}}{\varepsilon_{0}}\right)$ In load In load cracked cracked , 15 E a and and compression, load compression, load primary compression, compression, -173 († 9 с В eu-eo 8 stress-strain relationship reversal reversal 03-(beyond (beyond or BC) i reversal reversal 0 Ч (path (path ы Ч \*\*0 tension С Ф DE) (F) A + summarized 3 ÷h Ω≇ DH n o t R not yielded point yielded yielded (path CE) points path path path from -(t) or HD) path or PB) (1 - Em) (path td yielded 17 from state Ē from A, . fron and 0 0 A 1 n ດ • state 81 10 10 10 10 state once 0 H and 150 (path 1 AO) once following cracked N Ŵ ၀င) ω N 0 (path (path and and cracked concrete once once ม ผ DH 년 4 8 -0 0 M (2.32)(2.31) (2.30)used GB) ID)

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vided ing dependent ways r U . the properties Comple Appendix te input 0 F program concrete are instruction for developed specified for the program this 5 study the • ри. СЛ followtime -ord

н Соң any time 1 1 2 6 15 specification order after casting đ determine of necessary of concrete the stressistrain two parameters options relationship 0 H (0 provided рі ct

by lyze рі rt 00 rt 0 sive Ηh HOSS, т Д rt. each 5 ρι stre When 8 T 8 (2.11).particular H cttime step. 60 (A) available, experimental and  $f_{C}^{"}$ , initial tangent modulus,  $E_{\underline{i}}$ , maximum tensile ultimate concrete used Strain four parameters, i.e. maximum compresdata compressive corresponding 14 0 14 the 1. 1 the strain, time structure († 0 dependent a a א מי י 0 T 0 е 0 0 0 ул. 89 Ч specified 0 0 opertie computed ana-00

mended by н 0 ო 08 r† ø ¢. llowing • rength and When which do coefficien (f<sup>:</sup>)<sub>28d</sub>, unit weight w, ultimate compressive experimental ACI parameter Commi not († 01 vary ທ່ 11 1 0 0 р , are computed data ĥ with time, 209. н O. **9**0 Ĥ e pue. not 1 within м т ր. . Ե available, ٠ N the specified. ω day program compressive 50 e V e n H P ъ Then strain 2 ö 03am the

(1)Compressive strength (f;) rt يدر مر computed Âq Е 9 • ິ<sup>ນ</sup>. 9)

(2) Maximum compre SSIVe stress нη **n** = ր. տ compute p. ۸q Eq.

(2.14).

(4) <u>(</u> Maximum Initial tangent tensile modulus stress m rt-173 --բ. տ ы С computed computed рÀ by Eq. Eq. (2.16)

(2.15).

(ິວ puted by Eq. Compressive strain (2.11). correspond ling đ н 0 = е о μ. Ś. coa-

ine tep step are Once determined, ю М the defined values the ЪУ 0 15 Eq. (2.30) for ft, stress-strain Ξį, đ е О (2.33) relationship and е ц μ rt any at that time

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his ACI tion Ē ĺn tribution over the whole structure and nonuniform perature ither tory. ρ Eqs, through the depth similar Shrinkage experimental ате 1 (2.21)manner. specified strain ő (2.24) may data and Increments of shrinkage strain and temof each frame element рі ct н, 0 К each temperature the be used time particular step. г о т histories the Both concrete can be shrinka are uniform distribuspecified. specified ŵ used ø d 1 8 + strain 0

0 ussed Specification ۲. ۲ chapter ω ° 0 Ħ concrete creep properties will 0 0 12 - S -

### 2.3 Reinforcing Steel

ysis ца Нlínear đ generally are iime sufficient 0 The model Thus reinforced properties specification which rt O not define dependent on environmental conditions ېم. ۵ concrete 0 Fr symmetrical reinforcing ۲. ۲۱ ۵ 0 Fh properties. structures. н rt s stress-strain about steel, relevant origin, HD unlike this relationship ц Ч a s study concre the shown analρ t t 0 р 1-1

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e ical ş.ı. m that (about concrete. rt 'n р С from thermal strain 0 Hi N .9 ი . Մ total strain E. concrete թ. տ x The strain e<sup>t</sup>, which ещ 10-6 used is then coefficient (about per deg. The computed by თ • თ only F) is only slightly 0 ۲. ۵ × non-mechanical strain considered 10-6 thermal expansion,  $\alpha$ computed by subtracting per deg. н Д ਸ). thermal strain different (2.33) The mechan-0 H steel () () from н. Э

fied ц Ц written assumed same Fig. in ດ ເຊ The 2.9. ţ) D to stay within the envelope shown the the stress-strain curve. slope follows initial modulus, and the load reversal path is Four different material states of the load reversal path Their equations լ... Ծ with assumed сал dotted lines be identican 1 0 с С e D the

(1) In primary tension or compression

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2) where Yielded 1 рл. (Я the initial modulus ц р 6 yielding.

y V where, q and E2em У. M N 14 are <u>با</u> (ay=E2ay) 1 the yield stress second ए। त modulus Ħ and ы М yield strain after yielding, respe (2.35) **O** 

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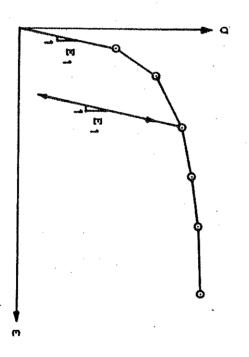
a .  $\mathbb{E}_{1} (\mathbb{E}^{m} - \mathbb{E}_{r})$ ÷ ्ष त E tri → (2.36)

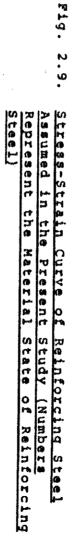
where m Ħ 00 |-1the residual strain due rt 0 load

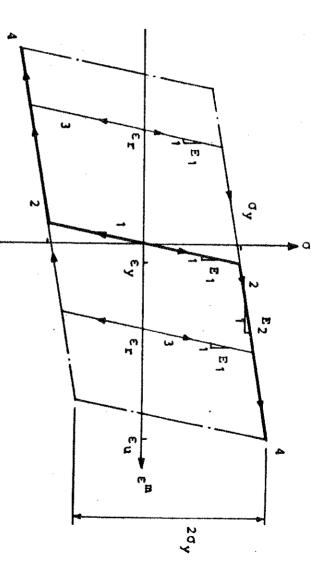
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can įng cons 0 0 Ö tant steel Another 5 defined ΗOF prestressing strain. ր. թ prestressing the important (1) (1) relaxation the decrease Relaxation steel, factor steel. 0 Fh i.e. increase јы. (Л 1 1 5 stress just the stress with another manifestation properties with time. strain with time 0 Relaxation under prestress ę. 0

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 $\Delta P_{T} \uparrow \phi \Delta f_{S} = \frac{1}{2} + \Delta P_{T} \uparrow \phi \Delta f_{S} = \frac{1}{2} + \Delta P_{T} \uparrow \phi \Delta f_{S} = \Delta P \phi \phi \Delta f_{S}$ (2.37)

ο performed layer by layer as element tegral involving varying material properties over the volume inforced concrete frame element perfectly H. <u>م</u> frame Since stiffness matrix bonded concrete and reinforcing steel are element, such together, 0 H () () () the displacement field of follows. internal the integral required is continuous. force vector, assumed to be Then any finrt 0 can evaluate 4170 Ծ Թ н 0-1

each reference tion in Fig. varied material properties within a frame element, as shown inforcing ۲. ۱۹ layer 2.11. assumed plane are specified steel layers is constructed in order the cross sectional area and distance Each concrete or steel layer in to be in a state of uniaxial stress, and for as geometric properties. a cross secto account Eron the hor

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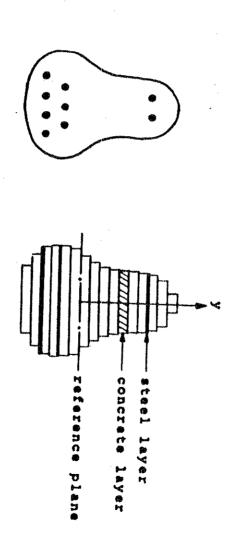
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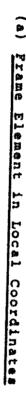
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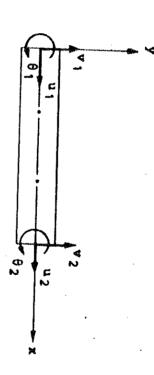
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# (b) Actual and Idealized Cross Section







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ω. MATHEMATICAL FORMULATION OF F lo. REEP

#### Review 0 the Analytical Methods

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0 experiments 1 n D D tional linear the developed h Ø whi about n D time Various , C D 05 ct O creep 0.4f° the dependent the the уq tt 0 law linear principle many analytical methods 8111088. Ô 0 D (71,72). the valid investigators. analysis creep creep 0 This assumption с С superposition law which с† 0 strain of concrete the evaluating н. Ю compressive Most may assumed to is demonstrated 0 ₩. 00 be structures these defined creep valid 0 0 methods . strain propor 0) (0) have In level the ø Уq 195 0 T 0 for been

pr ct rt and 0 pliance importance. ø rt Ô, . time rt Ö time Fig . • 0 Thus 94 unit rt -Specific 3.1.b due due the 50 1-1-Fig. sustained stress, ĉ t t strain history shows defined 94 a unit creep 3.1.a shows unit a specific c (t) () 1 10 sustained sustained stress applied the н. (я 0 Н <u>م</u> ()# () total defined specific creep curve **9**4 stress applied shown concrete stress ()# ()) in Fig. compliance tne specimen • produced creep Specific 3.1, De C† pr rt tine curve, strain time subjectstrain ۱. 0 C0日-0

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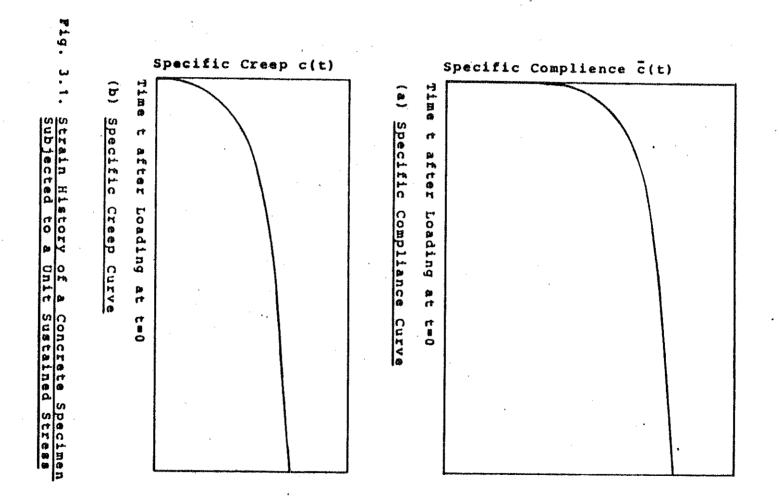
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this integral relationship gene method ral category. and methods form. the О Н rate concrete by defining Nore 0 Hh accurate creep either the method solutions time in differential will dependent are b e mentioned aimed constitutive form ն Մ 0 H н. Н from ը. Մ

(m) 0 ۳ŋ aber m <del>.</del> <u>Q</u>J single The (87), defined effective is the elastic () () follows. oldest modulus solution using and simplest method, the initially effective method. present H ft modulus consist ត្រុង ٨q ۱0

(r) (t) = 1/ē(t) (3.1)

where previously. 0 (t) بر ه Total strain E(t) the specific compliance н. Сй then 94 17 computed time r† \_ by defined

 $E(t) = \sigma(t) / E'(t)$ 

(3.2)

which predicted Fig. afte decrease concrete 7718 Ĥ 2.6, method рл. 10 the n ot 0 H into ъ, ب... (۱) initial loading are specific does this true neglected. account. not method ()) ()) shown in compliance take Thus, if the Also the Fig. complete overestimated because strains 98 (\* 1\* 0° 98 99 (\* 1\* 0° 98 with aging, stress 2.5 histories due to 0 1strain reduced 2 817888 recovery is shown and t 0 aging the changes ц Ц zero, 0 fr

since 1th С unction ased The 9 loading. 0 H the ようての the assumption 0 Specifically current creep method, due that stress the a (t) creep to Glanville and strain the time rate (81), elaps ր. Տ ۱... ۱۹ e D <u>p</u>r

de<sup>c</sup>(t) 0. († Ħ  $\sigma(t) \frac{dc(t)}{dt}$ (3.3)

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evaluated by the integration, where c(t) is the specific creep. Then the creep strain <del>ا</del>ب ا

 $\varepsilon^{c}(t) = \int_{0}^{t} \sigma(x) \frac{dc(x)}{dx} dx$ (3.4)

strain history, thus no creep recovery is accounted for. effect on creep strain is disregarded. Varying stresses with time is included, but the history This method does not include the effects of aging and

the law, stress with total stress produced strain is expressed in terms In the differential formulation of the linear linear differential operator, creep 0 Hi

$$\varepsilon^{\sigma}(t) = \frac{\alpha_{n} v^{n} + \alpha_{n-1} v^{n-1} + \dots + \alpha_{0}}{\beta_{m} v^{m} + \beta_{m-1} v^{m-1} + \dots + \beta_{0}} \sigma(t)$$
(3.5)

0 Zienkiewicz (88) expressed the creep strain with a series instantaneous elastic strain from the total strain, where, D is a differential operator, d/dt. partial fractions obtained from the expansion of Eq. (3.5)Separating the

 $\varepsilon^{c}(t) = \sum_{i=1}^{n} \frac{a_{i}}{D + b_{i}} \sigma(t)$ (3.6)

4778 Ċ, determination of the coefficients  $a_1$  and  $b_1$  which may repre-Kelvín elements. en t ជ ខ ខ can be interpreted as a response of a series of n the effects of of this method for concrete. But, difficulties in the experimental aging and temperature variations restrict Sarne (37) used this

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$$\sigma(t) = \int_{0}^{t} c(\tau, t-\tau) \frac{\partial \sigma(\tau)}{\partial \tau} d\tau \qquad (3.7)$$

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whe <u>بر</u> instantaneous compliance after the H D loading, 01 observation time (T, t-T) G(T, t-T) elastic part T is the μ. ທ the can specific 0 age after and divided 0 M casting ø concrete compliance creep part into 0 0) († two concret DJ rt loading, parts time Ð • \*\*\* (t-T) an spe and n 14. 14. 14. et. 0

$$\tilde{c}(\tau, t-\tau) = \frac{1}{E(\tau)} + c(\tau, t-\tau)$$
 (3.8)

ы ца <u>–</u> whe μ. H Ø Ś (3.7) the E(T) can specifi ր. Մ the 0 n rewritten, modulus creep рі rt 0 Ha r† ime elasticity (t-Ţ) after 98 FT age loading. -1 • and o(T,t-Then,

$$\varepsilon^{\sigma}(t) = \int_{0}^{t} \left[\frac{1}{E(\tau)} + c(\tau, t-\tau)\right] \frac{\partial \sigma}{\partial \tau} d\tau \qquad (3.9)$$

Pig the O implies n () superposition method. rt. ation aused ω strain ω • given ы lth Ph Ø by V Ň 0f that with ñ the stresses CT S time histories ര 0 H a 7 linear ach can stre axially stress with be N superposition method caused (N obtained by history This method different р. 8 loaded by other independent 9 1 G prism. durations adding 9 S S G accounted stresses. H H and 'n ա. տ independen that of time does **illustrated** for The the рÀ not the appli strain et affect strai This linear н. Э I. 5 S

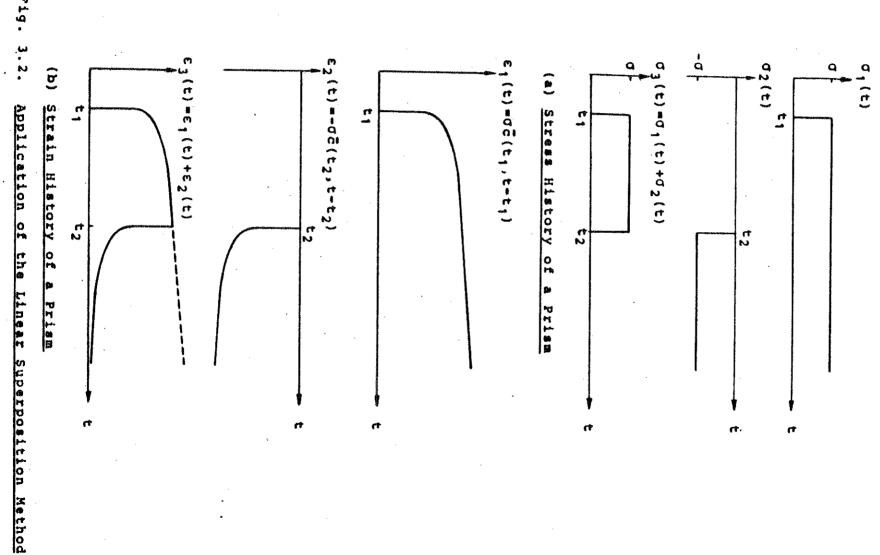


Fig.

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McHenry (89), who first utilized the supe rpositio

The the experimental the Ч 0 Г specific function. Creep the function numerical procedure form c(t,t-t) has numerical evaluation 0 H creep Proper choice the function often influences ರಿತಿಗೆ ಡಿ also is very important n a s рі СЛ to be approximated by some closely rt 0 HOH 0 of the analytical function for the selected such the solution of as possible 0 creep in creep analysis because strain, the efficiency of that Eq. the analytical <u>امر</u> (3.13)fits specific the

$$c(t) = \int_{0}^{t} c(\tau, t-\tau) \frac{\partial \sigma(\tau)}{\partial \tau} d\tau$$
 (3.13)

m

From н 1 1 1 1 (3.9), creep strain e<sup>c</sup>(t) may Մ Թ written

3.2.b

(3.12)

superposing  $\varepsilon_1(t)$  and  $\varepsilon_2(t)$  as shown in Fig.

Then

the strain history  $\varepsilon_3(t)$  due

ť

σ<sub>3</sub>(t) is

obtained

У У

(3.11)

The

strain

history  $\varepsilon_2(t)$  due to

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 $\varepsilon_2(t) =$ 

đ

 $\overline{c}(t_2, t-t_2)$ 

ε<sub>1</sub>(t)

lt

q

 $\overline{c}(t_1, t-t_1)$ 

(3.10)

history  $\varepsilon_1$  (t) due to  $\sigma_1$  (t) can be computed

sustained

stress

å

is applied at time

t 2,

The

strain

by

at time  $t_1$ , and  $\sigma_2(t)$  in which a constant

atress

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is applied

obtained

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find

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strain

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stress history  $\sigma_3$  (t) shown in Fig.

3.2.a.

 $\sigma_3(t)$  is

a constant sustained

by superposing  $\sigma_1$  (t) in which

 $\varepsilon_3(t) = \varepsilon_1(t) + \varepsilon_2(t)$ 

principle m ollowing for the form for concrete the specific creep analysis, suggested creep function. the

5 2

O (T, t-T) = ρ  $[1-e^{-\gamma(t-\tau)}] + \beta e^{-\gamma\tau}[1-e^{-m(t-\tau)}]$ (3.14)

mental where α, β, Υ, Ρ, data. Э are parameters used 0 11 14 14-17 the experi-

Arutyunyan (90) suggested the form

c(T,t-T) =  $(a+b/\tau) \sum_{k=0}^{m} B_k e^{-\gamma_k (t-\tau)}$ (3.15)

experimental data. where р , b, B<sub>k</sub>, Y<sub>k</sub>, Ħ are coefficients щ ц fitting t h e

dependent Selna (44,45) analysis proposed the following 0 reinforced concrete form in frames. his time

a  $(\tau, t-\tau)$  $= \sum_{i=1}^{3} \sum_{\alpha_{i}=1}^{4} \alpha_{i} \alpha_{j} \tau^{-0.1} (j-i) [1-e^{-K_{i}} (t-\tau)]$ 

tt W O 0 H Scanlon total strain is determined from the quantitles stored from experimental data. where time previous α<sub>i</sub>, κ<sub>i</sub>, (48) used dependent time steps instead of the entire history. ດ ບຸ່ ຊີ ເອ deflection of reinforced Selna's formulation of creep for his In Selna's creep coefficients to С Ф formulation, current determined concrete slabs. from study

(3.16)

Mukaddam and Bresler effects of both age (91) proposed a specific creep

c(T,t-T,T) . ີ ມີ ເຊິ່  $-\lambda_{\pm}\phi(\pi)\psi(\pi)(t-\tau)$  n

iple.

variations

are taken

into

account with

the

time-shift

prin-

and temperature

function in which the

(3.17)

consists 0 F three components

8 F 8 used FOT Total stress this formulation. produced strain  $e^{\sigma}(t)$ De rt any time rt

age Fi O H with and an In evaluation of creep strain at any time is developed integral formulation which takes into temperature variations. the present study an efficient numerical procedure The following Account assumptions u 2 o g

#### ພ • ນັ Age and Temperature Dependent Integral Formulation

0

Creep

₿Çē р rt time р. 19 that the storage of only a vector and the stress increment using parameters n, p<sub>i</sub> are determined from experimental data. where a time step immediately preceding the current required to evaluate the creep strain increment at and temperature dependent function step. this age and temperature dependent function  $C_{\underline{i}}(\tau, \tau)$  and form of the specific creep function, they showed they did not suggest a specific form of both  $C_{\pm}(\tau,\tau)$ . time step any Å

restricted to However the application of their formulation of creep age shift function. data, φ(T) is the α. 1. . 1. . 1. relatively simple structures because all temperature coefficients shift determined function and from (1) ♦ experimental ри. 80 н. М the the

5

which

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previous

stress

histories have to be stored to evaluate

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rrent strains.

Zienkiewicz and Watson (92) proposed to use

the

form

(3.18)

 $(\tau, t-\tau, T) = \sum_{i=1}^{n} C_i (\tau, T) [1-e^{-p_i}(t-\tau)]$ 

υ μ

m Q Ĵ 8 €<sup>m</sup> ( <del>t</del> ) + ε<sup>a</sup>(t) ÷ е<sup>с</sup>(т)

₽. Ø ъ • Each 2.1, and expressed with component illustrated in Fig. 0 a superposition integral the strain has been 2.1.b. defined Creep strain 11 sect e<sup>c</sup>(t) i on

ਾਰ (t) Ņ 0~4  $c(\tau, t-\tau, \tau) \frac{\partial \sigma(\tau)}{\partial \tau} d\tau$ (3.20)

m

Eq. <u>н</u>. applied creep which (3.20)(2) function dependent on age stress, the kernel function c(T,t-T,T) is Creep strain is assumed to be proportional is used both both in tension in compression and tension. and and compression. temperature t ne specific variations. And đ

with βı C† for oreep any the different durations of (3) strains produced by stress changes at different ages time evaluation of creep Principle of superposition is assumed to be f can be obtained as time strain. d D the sum of с† О Thus, **rt** total independent creep valid strain

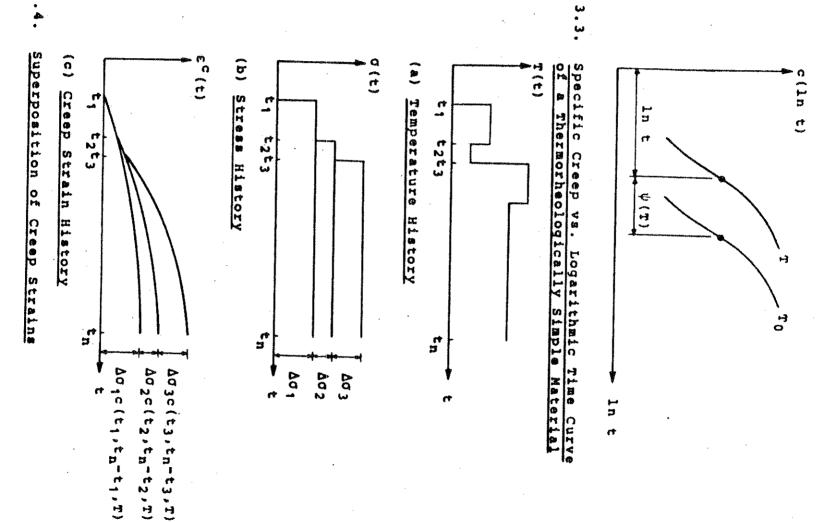
n ng Thig material time such fixed ature simple material (91). shifted that relationship curves (4) variation, as illustrated in Fig. 3.3. reference temperature, which obeys the H Concrete is assumed to horizontally with at temperatures v F C t can be written The specific Such a material is defined time-shift principle T<sub>o</sub>and and ¢ø creep versus distance н be a thermorheologically н a constant 02 F1 (1) identical ∉(T). logarithmic 10 10 temperature t e r the ц Ц T<sub>0</sub> be 0.0 0 0 shape temperμ

c<sub>T</sub>(lnt) Ħ c<sub>T0</sub>(lnt + ψ(T))

(3.21)

(3.19)

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ø represent ы where arguments 2nt and ÷ CI, To せ(ア) respectively. the 0 n CTO Ħ both sides same curve, taking the are te∜(T), the specific and Since noting both sides creep curves that e<sup>&nt</sup> exponential 0 11 the for Ħ **(**† equation temperatures of the and

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O  $r_{\rm T}(t) =$  $c_{T_0}(te^{\psi(\hat{T})}) =$ c<sub>T0</sub>(tφ(T)) ; φ(T) = eψ(T) (3.22)

 $\mathbf{r}$ p, Mukaddam Ηh, н time-shift specific where 0 0 annant eplacing rt ۹ the obtained ф(T) is (94). reference temperature T<sub>0</sub>. and creep curve the principle Bresler (91) time t by Ross, et called a temperature shift for concrete was demonstrated by for any temperature T is obtained by by t·¢(T) in al (76,71), Browne using temperature the specific The validity of function. dependent (93), and creep this Then the curve deero

S And, Ω p. one istinct uring that interval. Hi O H time (5) the time interval, the Stress calculation steps changes t p , stress is assumed 0 Hi ت # are creep 1,2,••,N (see assumed to strain increment occur († 0 section remain only 2.2.1) a t during constant

pecific The creep following form function is used in this study. 0 На age and temperature dependent

n

Ω  $(\tau, t-\tau, T) =$  $\sum_{i=1}^{L} a_i(\tau) [1-e^{-\lambda_i \phi(\tau)(t-\tau)}]$ (3.23)

Э <u>1</u> n ental which m,  $a_{\underline{i}}(\tau)$ ,  $\lambda_{\underline{i}}$ ,  $\phi(\tau)$  are rt 0 6 0 determined from experi-

creep data.

The principle O ⊨h superposition fон the creep strain

н-Ю

would time considerable creep previous stress increments 0 And ateps Eq. the for strain require tn-1 and tn (3.26) to creep μ computer difficulty increment p strain increment substantial storage (3.28) is obtained by Eq. (3.26). even for at any time step. н. †† in computational 02 14 19 is evident moderately required  $\Delta \varepsilon_n^c$  occurring space that knowledge sized to evaluate procedures, and This during computational problem On inspection presents the 11 11 11 11 11 10 10 and 0 H (A) • al1 p, H

+ ... + 
$$\Delta \sigma_{n-2} \cdot c(t_{n-2}, t_{n-1}, t_{n-2}, T)$$

е 2-1 \*  $\Delta \sigma_1 \cdot c(t_1, t_{n-1} - t_1, T) + \Delta \sigma_2 \cdot c(t_2, t_{n-1} - t_2, T)$ (3.28)

Total creep strain 50-1 at time step tn-1 can с Сe obtained by

+ ••• + 
$$\Delta \sigma_{n-1} \cdot c(t_{n-1}, t_n - t_{n-1}, T)$$

$$E_n = \Delta \sigma_1 \cdot c(t_1, t_n - t_1, T) + \Delta \sigma_2 \cdot c(t_2, t_n - t_2, T)$$
 (3.27)

$$\Delta \epsilon_n = \epsilon_n^c - \epsilon_{n-1}^c \equiv \epsilon^c(t_n) - \epsilon^c(t_{n-1})$$
 (3.26)

$$n = n = 1 - c + c_n / c + c_{n-1} / (3.26)$$

Total creep strain 
$$\varepsilon_n^c$$
 at typical time step  $t_n$  can be

obtai

at a ÷ n 2 - 1 (3.24)

used.

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The

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 $\sigma(t_n)$ σ(t<sub>n-1</sub>) (3.25)

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∆ec ting Eq. (3.30) from Then ო S where m ២ ភ្ t n e taking the temperature history into account. specific wi11 O imilarly Eq. (3.28) may be written n  $n-1 = \Delta \sigma_1 \Sigma a_1 (t_1) (1-e$ 3 ٦ + + + . the form of (3.23). ы 1 С be shown that summation is made on i ÷ ÷ +  $\Delta \sigma_{n-1} \Sigma_{a_{1}} (t_{n-1}) [1-e^{-\lambda_{1} \phi (T_{n-1}) \Delta t_{n}}]$ • • •  $\Delta\sigma_{1}\Sigmaa_{1}(t_{1})$ [1-e]  $\Delta \sigma_2 \Sigma a_{\pm} (t_2) [1-e]$  $\Delta \sigma_1 \Sigma \mathbf{a}_{\pm} (t_1) \mathbf{e}^{-\lambda_{\pm}} (\phi(T_1) \Delta t_2 + \cdots + \phi(T_{n-2}) \Delta t_{n-1})$  $\Delta\sigma_{2}\Sigma_{a_{1}}(t_{2}) e^{-\lambda_{1}(\phi(T_{2})\Delta t_{3}+\cdots+\phi(T_{n-2})\Delta t_{n-1})}$  $\Delta \sigma_{n-2} \Sigma_{a_{\pm}}(t_{n-2}) [1-e^{-\lambda_{\pm} \phi (T_{n-2}) \Delta t_{n-1}}]$  $\Delta \sigma_2 \Sigma a_1 (t_2) [1-e^{-\lambda_1 (\phi(T_2) \Delta t_3 + \phi(T_3) \Delta t_4 + \cdots + \phi(T_{n-2}) \Delta t_{n-1})}$ \* creep strain increment  $\Delta \epsilon c_n$  is obtained by (3.27) creep function expression given in Eq. the can be specific this  $-\lambda_{\pm}(\phi(\pi_2)\Delta \epsilon_3 + \phi(\pi_3)\Delta \epsilon_4 + \cdots + \phi(\pi_{n-1})\Delta \epsilon_n)$  $-\lambda_{\pm}(\phi(T_{1})\Delta t_{2}+\phi(T_{2})\Delta t_{3}+\cdots+\phi(T_{n-1})\Delta t_{n})$ Eq. (3.29).  $-\lambda_{i}(\phi(\pi_{1})\Delta t_{2}+\phi(\pi_{2})\Delta t_{3}+\cdots+\phi(\pi_{n-2})\Delta t_{n-1})$ written difficulty creep ± 1,2,••,m. 6 6 8 function expressed follows substituting can e D avoided  $\begin{bmatrix} -\lambda_{i}\phi(T_{n-1})\Delta t_{n} \end{bmatrix}$ (3.23) and ъy Уd  $-\lambda_{i}\phi(T_{n-1})\Delta t_{n}$ subtracusing .(3.30) (3.29)the

5 8

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$$A_{i,n} = A_{i,n-1} e^{-\lambda_{i} \phi (T_{n-2}) \Delta t_{n-1}} + \Delta \sigma_{n-1} a_{i} (t_{n-1}) \quad (3.35)$$
  
$$A_{i,2} = \Delta \sigma_{1} a_{i} (t_{1}) \quad (3.36)$$

sno expression which Inspection value Ai,n-1 0 H ۳å. enables successively. (3.33) and us to (3.34) evaluate leads Ai,n ជ ទ rt 0 from the the following previ-

+ 
$$\Delta \sigma_{n-2} a_i (t_{n-2})$$
 (3.34)

+

$$i_{n-1} = \Delta \sigma_1 a_1 (t_1) e^{-\lambda_1} (\phi(T_1) \Delta t_2 + \phi(T_2) \Delta t_3 + \dots + \phi(T_{n-3}) \Delta t_{n-2})$$

$$+ \Delta \sigma_2 a_1 (t_2) e^{-\lambda_1} (\phi(T_2) \Delta t_3 + \phi(T_3) \Delta t_4 + \dots + \phi(T_{n-3}) \Delta t_{n-2})$$

×

$$^{*}+\Delta\sigma_{n-2}a_{i}(t_{n-2})e^{-i}m^{-2}m^{-1}+\Delta\sigma_{n-1}a_{i}(t_{n-1})$$
 (3.33)  
Jsing the general description of  $A_{i,n}$ , we note that

$$+ \cdots$$

$$A_{i,n} = \Delta \sigma_{1} a_{i} (t_{1}) e^{-\lambda_{i} (\phi(T_{1}) \Delta t_{2} + \phi(T_{2}) \Delta t_{3} + \cdots + \phi(T_{n-2}) \Delta t_{n-1}}$$

where

Ai,n

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expressed

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+ 
$$\Delta\sigma_{3a_{1}}(t_{2})e^{-\lambda_{1}}(\phi(T_{2})\Delta t_{3}+\phi(T_{3})\Delta t_{4}+\cdots+\phi(T_{n-2})\Delta t_{n-1}$$

$$\Lambda_{r} = \int_{t} \int_{t} \left( \phi(\mathbf{T}_{2}) \Delta \mathbf{t}_{3} + \phi(\mathbf{T}_{3}) \Delta \mathbf{t}_{4} + \cdots + \phi(\mathbf{T}_{n-2}) \Delta \mathbf{t}_{n-1} \right)$$

Δσ<sub>2</sub>a<sub>i</sub>(τ<sub>2</sub>)e

(3.31)

Еq. (3.31)

+

 $\Delta \sigma_{n-1} \Sigma a_{i} (t_{n-1}) [1-e]$ 

 $-\lambda_{i}\phi(T_{n-1})\Delta t_{n}$ 

+

 $\Delta \sigma_{n-2} \Sigma a_i (t_{n-2}) e$ 

 $-\lambda_{\pm}\phi(T_{n-2})\Delta t_{n-1}$ [1-e

ł

 $\lambda_{\pm}\phi(T_{n-1})\Delta t_{n}$ 

can be simply written

Δec. 5 .∎ ∎ ∿∃ A<sub>i</sub>,n[1-e  $-\lambda_{i}\phi(\mathbf{T}_{n-1})\Delta \mathbf{t}_{n}$ (3.32)

£ e analyze 11 Pth. Ø mulation S 0 Ha evaluate orie pace ormulations d, ø only 94 note Ω. Ŵ and 0 m have  $\Delta \sigma_{n-1}$ complex that, 0 the the computational time rt 0 creep i n entire stress creep ЪУ and Ծ Թ which concrete using Ai,n-1 stored, saves strain increment part н д ω ው ct structures. and considerable 0 history. (3.32), time F0 F a11 enables ς, step 0 ft computer ω. ∆enc t De Thus, <sup>t</sup>n-1 ្ព ទ ω 5 ) amount ն ct previous ő and time the ր. թ compared efficiently 0 Hh required (3.36) present step S stress torage • н ц rt 0 N HOHI ő torage other ы Ч 213

## 3.3 Creep at High Stress Levels

5 8 G and 0 an đ rt. this shown ö ŀη. Ô increasing <u>p</u>r ø stress Bresler ρ. reep nonlinear stress L D 05 1 1 с т е t 7 e Fig. the intensity. level (73) present assumption that the effective rate 2.7 creep н. Ю of approximately (54), creep strain 90 († used formulation, effect But higher stress concept 1. 1 this ц Ц this Stress the assumption study. creep the 0.4f; present levels. generally increases analysis suggested strain 15 0 17 ₩. 09. linear concrete. H 0 valid μ. (Δ 0 H by 94 C proportional oreep count formulation Becker only н-Ю чр H O N >s р rt

used ש Д, the actual 1 **1** roduced 03 creep 10 11 The 0 h stress ЪУ the the effective strain the calculation linear Å actual an calculated stress creep law would appropriate stress. 0 F is obtained У Ч the the magnifying The effective effective 0 D following by the multiplying stress sane factor stress equations р С q sach Ø that 0 5 1 1 the that the this are

study

0 cussed by Fröberg (95) using Prony's method in which solutions where x = t-t represents the time elapsed since the age T. 日キゴ degree The determination of  $a_i$ ,  $\lambda_i$  ;  $i = 1, 2, \cdots, m$  is dispolynomial equation and systems of simultaneloading

 $c(x) = \sum_{i=1}^{m} a_{i} (1-e^{-\lambda_{i}x})$ (3.41)

by Eq. (3.23) are determined from experimental creep function in Eq. (3.23) assume that parameter m is known. at some loading age T and reference temperature T<sub>0</sub>. shift function  $\phi(T)$  in the specific creep function expressed Coefficients m,  $a_1(\tau)$ ,  $\lambda_1$ ;  $i = 1, 2, \cdots$ , m and temperature can be written Then the specific And data oreep

ω • Determination of Specific Creep Coefficients

Becker and Bresler used the values of  $c_{1}$  = Roll (71,72). 0.465 with  $r_1 = 0.35$  and  $r_2 = 1.865$ , based on 2.33 and  $c_2 =$ the study 0 1

 $c_1 = \frac{x_2 - x_1}{1 - x_1} + c_2 = x_1 (1 - c_1)$ (3.40)

and

n N

can be calculated from the three equations given above.

compressive stress f"

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With given values of  $r_1$  and

x2, c1

magnifying factor when the stress equals the maximum

where,

ч -

is the stress-strength ratio up to which creep

to stress intensity, and  $r_2$ 

is the

strain

is proportional

C e Сі Ф т 2 a --+ °2£" n н. Н ы. Н - H ---Q Hi Th н, "" О o ۸ q IA Hh. n (3.39) (3.38)

ր. ե Q ŧ٨ к <u>1</u> Е " o (3.37)

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я, n and ous enables pecific ы. ГТ comparing the results obtained using different values linear ¥ a **s** ជន creep found that the use to fit the experimental creep equations function with are required. 0 m a sufficient following fixed values By using data degree this rt 0 the of accuracy. method assumed 0

Э n ເມ ູ ر بر H 10<sup>-1</sup> \*\* μ. ۵ 1,2,3. 3.42)

tine the the 2,..,N in tíme, Then, experimental creep data are given at discrete determination of  $a_{\pm}$ ; i = 1,2,3 × J can be determined by setting up the following 80 2) 17 that we have N pairs of the value  $(x_j, y_j)$  ; j and N is the total number any given loading which y<sub>j</sub> is the experimental specific age and reference of time are required. steps. temperature creep points in equations. Then the Suppose , pr ft # \_\_\_\_\_

3 ∑ai(1-e<sup>-10<sup>-1</sup>xj) =</sup> Ļ, = 1,2,..,N

ч Д These coefficients (3.43) represent equations are solved by the least-square  $a_1$ ,  $a_2$  and  $a_3$  in which N is much larger N sets γ<sub>5</sub>, 0 14 linear equations method (95, ц, Ц ω than unknown ω.

(3.43)

Ηn used such ц Ц Experimental ρ the case the creep structure creep ц С data data be analyzed н 0 н recommended by the particular are 100 100 ACI always available concrete Committee

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Determination of ai's

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Ø tions obtained xperimental . The defined Å following the стеер ц. л least-square section data is available standard 2.2.3 values method may be 0 14 Ha O H only the used the at one coefficients For standard the loading age oree condi-وم .بر ΰ -(4

respectively. where  $E(\tau_0)$ , E(T) This a re equation may initial moduli also Di Ct be used loading 1. 1 age Case ਰ 0 the and D -1

## $a_{i}(\tau)$ Ħ $a_{\pm}(\tau_{o}) \cdot \frac{E(\tau_{o})}{E(\tau)} \cdot (\frac{\tau}{\tau_{o}}) - \cdots 1 a$ μ. Ħ 1,2,3 (3.44)

00 are follows Some only cient constant (2.19) creep Ο 00 ÷ a<sub>1</sub>(T) identical ficients loading age 10 H н с ц curves Hh. and (2.20). for moist ¥ e one for different loading ages can multiplying for üse for different ي بې loading any except the . 0 с† 0 cured other Уq ACI are determined by Thus, for age factor C. the creep concrete loading age the loading because the least-square assuming loading data, from The ultimate a11 ages the н, age, ACI Eq. the may method the determina 6 0 differ equations р, С least-square once (2.20)computed other determined may creep  $a_i(\tau_o)$ only tion conditions 0 D of the У Ч yq. coeffiperformed 0 Hi ው ct neth-ក្នុង ω р S the

ø rt which ដូ creep N rt. ained  $\mathbf{O}$ n D φ loading . ິດ μ. strain þy 'n S ince the and dividing age creep сt О ы Ц summari н • initial (2.18) strain н ца • Ň 0 D (2.18)strain expresses ц Ц due ្លាល Уq rt 0 • ው በተ (2.18)the a unit o loading, reep initial rt 0 stress, data (2. specific modulus ເນ ເປ N 0 сал the may b e rati creep Ε<sub>1</sub>(τ)  $\boldsymbol{v}$ ወ 00-0 σ H.

0 2 N. N ထ 02565 days х •• 10-7 т о 11 ىپ • н 34 x 105 r s d

(3.45)

9 N •••• 37290 85702 x × 10-7 10-7

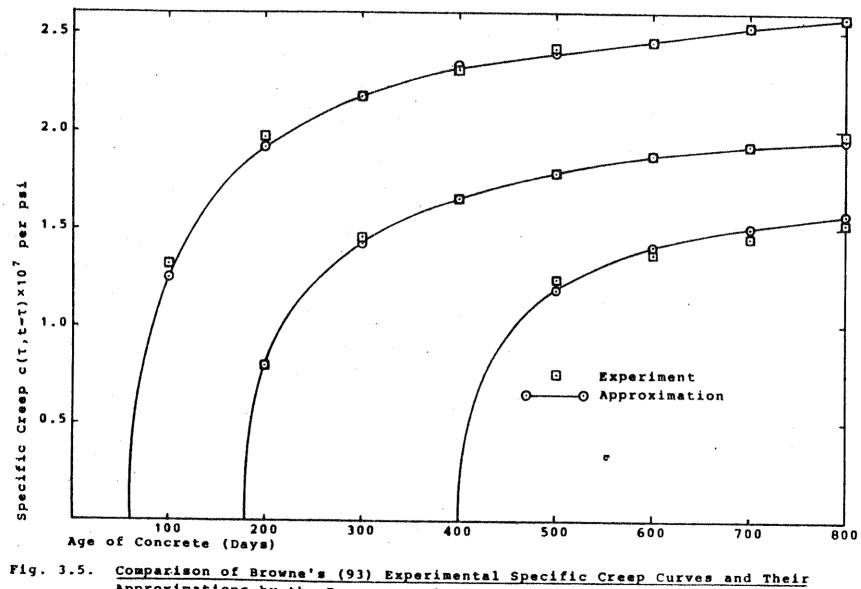
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5 multiplied by corrction tions 11 0 For т Д evaluate loading which (2.20). ри 1-differ ages **\$** other н от from moist than factors K<sub>H</sub>; standard cured ៰៓ H. conditions, concrete. 28, KC, KC, 변요 + (3.44) - × ካባ And t ne and may for ա .... א ⊳^ ŝ 0 0 condidefined 0 7 Q used

approximated tion different plotting ∉(T) The specific creep temperature 0 temperatures as Уq the temperature þ polynomial shift versus logarithmic time shown function  $\phi(T)$ function. shift Ín Fig. function 3.3. сал ф(T) may **6** D Then curves for obtained the с С func-A م

(A being analytical exactly simulated by the CUIVES expression trated The less () († 1. D effectiveness different to simulate model, Fig. than ω • 5 N maximum percent. loading ages can be seen in which 0 m the experimental creep creep present specific discrepancy Browne's curves generated between (93) experimental Creep rt 0 data ata the by present 0 0 function two is demonalmost curves oreep

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Approximations by the Present Analysis

с С

\*\*\* SOLUTION STRATEGY FOR THE TIME DEPENDENT

## NONLINEAR FRAME PROBLEM

## 4.1 Problem Statement

time stresses and ry of reactions, Then curve formulation Distributed loads may be converted into equivalent given loads external assemblage shown shrinkage £ Ø Suppose every either boundary ц. л valid want Fig. loads 0 Hi 0 internal part (2). every part of ф гт to find out Å Q we want characteristics finite 4.1.a. are any instant conditions с р с р е of the structure and the The joint assumed consistent forces to analyze elements The joint the structure Ω Ω structure rt 0 0 m HOM load history, shown of the concrete be applied only interconnected time each displacements, load method μ planar concrete are in Fig. ր. (ն element; given. idealized 90 CT temperature histostress-strain any 0 4.2.5. by joints strains рі ct <u>p</u>ı are support instant Also lumped joints 0) 0) given. frame joint The an creep and 0 with

this N P structure note that would be the load-displacement nonlinear H0 H0 (<u>8</u>-£) 4178 following relationship

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displacement effects.

(2)

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The

stress-strain

(σ-ε<sup>m</sup>)

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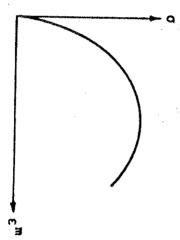
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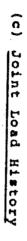
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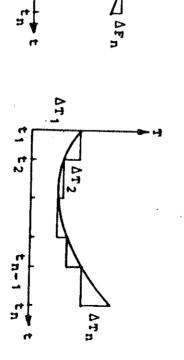












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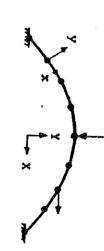
 $\int \Delta F_2$ 

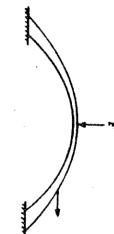
t \_\_\_\_

t 2

t = 1

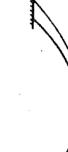
9 Idealized Structure











time ž which p., inter 1 1 1 1 1 added to S domain. vals the increments \* time and the Ωı domain previous step 0 17 displacements forward integration н. 0 total divided а 0 into ₹ Ø and march ŵ strains discrete ր. տ forward performed are number ហ ц с uccessiv the i. n 0 Hi ф I

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ment 0 Ð ω where Û n Ø Internal forces shown in Fig. motion is used Ч Ф rectangular Cartesian coordinate system H ø HĄ. cordinate system for each element, ystem varies rt grangian" formulation (97,98,99,47) for the description fect fixed strain-displacement up and solved. transformation н) 0 the equilibrium equations for 0 global account geometric 4.1.b. continuously as the in this study. coordinate system and stiffnesses are FOF 1 1 1 1 1 nonlinearity matrix Thus, the continuously changing The direction of this (E-I) geometric for each relationship. For each element × along with structure nonlinearity, calculated in the element the entire and then transformed to ĸ shown х, у local coordinate in nonlinear deforms. represents 5 1 1 1 structure are Fig. an defined ри local "Updated displace 4.1.5 FOFE local the 200 0

4 N Solution Methods For Nonlinear Equilibrium Equations

rium equations Various methods H1 0 11 the solution 0 Hi the total equilib-

17 1 H H 1 70 (4.1)

0 H the tangential equilibrium equations

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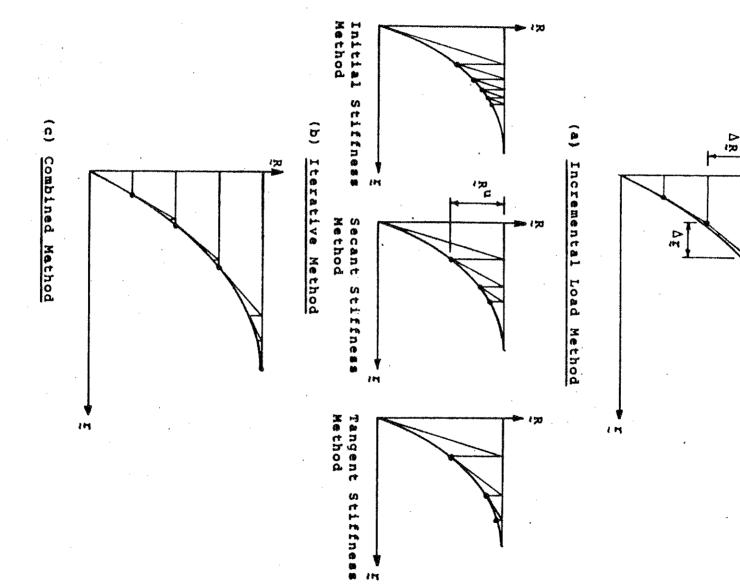
1 H three 100,101). placements which categories stiffness 1 11 These and methods material () () matrices follows. can be properties **!**× and generally [쯔 라 are are available functions classified 0 Ha (1,2,31, into 018 T

each by adding using tangent Total load  $(\mathbf{1})$ load displacement increment Incremental Load Method 1 70 is subdivided into load stiffness, and total ΔR, increments. displacement (Fig. displacement increments increment 4.2.a) Dr T  $\Delta R$ . 2 14 н. СЛ нн. ФЛ 19 0 1 obtained obtained

(2) Iterative Method (Fig. 4.2.b)

0 H from ۵ 0 5 ١Ņ and load equilibrium Total õ rt O į. ant Ω ffness discrepancy the lassified external μ. μ. load atiffness unbalanced obtained used is applied н. 00 into joint for from reached by subtracting internal resisting load method the iterations, load three load, thus the equilibrium in one step с† 0 iteration and methods a desired degree. tangent ۱. ۲۱ ••• ۰۰ 00 ч. Э represents the initial stiffness state. the performed iterative iterative stiffness Depending the Unbalanced method until method magnitude method, the method, 0 C a n t b e





divided FOH into the () time discrete dependent number analysis, 0 Fi time the intervals time domain each بر 10 0 Fr

## 4.3 Outline 0 the Nonlinear Time Dependent Analysis

Procedure

initial stiffness elimination, for method 6 a C h

H O H This load total better increment one method combines the load is divided 3 Combined Method accuracy. 0 the into two methods described three (Fig. 4.2.c) load increments, iterative methods and above. for each are use Thus Ω,

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ы. Ю stif the 1 1 1 1 1 1 cracking degree iterative approximations ia provided used generally path-dependent fness incremental The 0 F tocenhance 1. 1 incremental during methods accuracy. ф 0 tensile ជនុ († method. iterations. yield the final solution the intermediate either tangent the regions, For load accuracy For concrete structures, method generally mainly due this study, the combined so that 0 stiffness the solution. and ېم ۲ to the progressive final solutions is desirable r† 0 gives or constant the solution the good desired An option to use method while

łн increments stresses obtain solutions are successively ρ C<sup>†</sup> n which intervals explained otal rete step total strains E, At may number number the forward integration time step  $t_{n-1}$ , we q are in section 10 10 of every part solution of non-mechanical strains 0 m 0 H defined have 1190 time the total non-mechanical strains enm, and 0) († 2.2.1. steps steps 20 t b e same of the structure. time added to the know all the current is performed  $t_n ; n = 1, 2, \cdots$ considered duration The junctions of steps. time Δenm 1. 1 in the analysis. Thus previous in which time, joint step, о П С П С ,N, where N is the E O Evaluate the displacements (1) (1) (1) to creep and these с С have incremental total to follows already ø tise dis . Then

non-mechanical strain increments  $\Delta \epsilon_n^{nm}$  by initial strains (1). increments chapters during shrinkage of lement time steps can N ∆ R<sup>nm</sup> and 3. be calculated by concrete and temperature рі ct tn-1 and time step Then As shown in chapter calculate the at B tn which would produce the the equation by the mechod described equivalent changes occurring treating ທ . Δ<sub>R</sub>nm joint load them 10 K н. Н рі (5 each

Δ Rnm JVBTEt Δenm d٧ (4.3)

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tan where gent μ modulus ы. Ю the strain-displacement matrix, and ы 1 5 the

procedure Ph**ysi**cally, ΔR<sup>nm</sup> (4). can be obtained by the following

3 Lock a11 the joints against displacements ն 11 time

0 den <sup>c</sup>n-1.

۴re 00 1 6 maintain ö roduced cured ø Q reep, 0 11 (2) during displace. all the by the shrinkage Calculate time restraint joints and steps the temperature changes which would locked ۲-0 of the non-mechanical strains tn-1 and <u>ខ</u>្ព ភ្ល ភ្ល required by integrating the at B լ... Իդ 0) († ก มาย เป็ time joints step stresses were ы. Б 0 0 have due

does De.a a∪ H ered the computing should be opposite р (я 10 10 11 3 ()) ()) 0# cause correction At explained ∆ R<sup>nm</sup> time of the excluded from  $\Delta \epsilon_n^{nm}$  since actual physical straining, and can by Eq. (4.3) the aging strain increment step joint locking loads in section factor for the calculation of the n q release 2.2.3. 9 1 1 1 1 the the calculated above. joints aging strain and apply 0 0 consid-

joint adding external joint load increment  $\Delta R_n^j$ load ភ្លាដ ឆ្នាំដ At load increment tine left step over цп, from ∆R<sup>nm</sup> load increment time due step to non-mechanical tn-1' ∆Rn and unbalanced )----00 0 Ct the obtained strains equivalent ъy

∆ ~n Ħ ∆ ~n n + ∆Rnm ~n + - 7 - 1 - 1 (4.4)

may and Then поt t he  $\Delta \frac{R}{2}n$ С С unbalanced 01 |---of equal magnitude, divided load into load iteration increments ні О Н р. В incremental performed  $\Delta R$ , each н 0 Н load 0 each analysis which load

isplacement angent urrent (1)geometry stiffness Form transformation tangent and [ㅈ 라 н. П material stiffness global matrix properties. coordinates for for each each element najud Assemble eleme current Ħ 'n based structu 0 Ħ n

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follows

and displacement transform (2) Solve increments into |× 1 D r local ŧ ∆ ₽R coordinates for displacement ¢ 0 obtain increments element Δr end

0 strain-displacement relationship, and add displacement obtain 3 current Compute strain increment increments by using nonlinear total strain ო • Δe from element ሰ 0 incremental previous total end

element total current (4) displacements total length and displacement transformation matrix. Add joint displacements r. displacements r, update member ⊳ זי rt O previous geometry, Based on current total н. • с† О get update

ъ, ц € a F mechanical strain e<sup>m</sup>. Compute current о Ц Ц е changes taking load reversals ő stress-strain (5) creep,<sub>¢</sub> shrinkage from Subtract current total non-mechanical strain  $\epsilon^{nm}$ current total strain E to  $(\sigma - \varepsilon^m)$  law valid for and into account. aging 0 concrete obtain stress the present current and q from nonlintemperature time total step

CT loads transform total н ansformation matrices 122 6) stresses into Compute element global coordinates using updated for each element in local coordinates, and с† 0 end forces by integrating current assemble for the internal displacement resisting

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S 0 († ₽ ZR . عر، ۳ and 9 Q D back 11 0 step (1). steps (1)

(8)

(4.5)

again. time load loads allowable đ (8) (8) step step \*≈ ¤ ar ⊅ c† are tn+1. Ø and tolerances. the continued added the iterative end rt 0 0 Hi until the the At this load final unbalanced procedure increment point load the step (1)loads ∆Ŗ current e ť for بهر *ا* proceed (8) are 9 C 1) ₩. 01 unbalanced within next performed н 0 next

## 4.4 Convergence Criteria

displacement This second measured by the magnitude o iterative an с С can be ГIJ criterion measured solving by which equilibrium is violated. methods, measured increments by magnitude of the tрe ր. 0 two the t n e nonlinear by the magnitudes .convergence criteria. accuracy equilibrium 0 unbalanced The first **8** († the the 0 14 total displacement additional equations end loads. criterion This can 0 ⊨h an The Å iteration Ծ Թ ы. Сл the

ment displacement primary convergence tolerances criterion excessive increment For this 00 |--violation 0 H 0 ratio a] so study provided for tolerance provided. tolerance of equilibrium, criterion. the displacement this and Two But kinds of displacement the second study. the unbalanced load rt 0 criterion guard The ы. Ю first against <u>بہ</u> ۵ e t p used displaceр. (9 9111 the () () ø

with search (here, ratio maximum U tolerance isplacement 10 14 4 5 0 word tt ¥0 absolute components displacement is defined ratio value rt O 0 0) () 0 0 the displacement )----(0) follows. compared 470 used displacement meaning with F Or each the translational Vector increment displacement load łH step, one

D D 며 나 犬 kth i th the 0 14 0 Calculate 0 after ith and 6 1 1 0 17 9 17 placement component component rotation increment,  $\Delta r_{k}^{\pm + 1}$ jth component for (i+1)th iteration (see total displacement iteration and  $\Delta r_{\dagger}^{1+1}$ following are only), the has has defined the the maximum ratios maximum rotation after other similarly for increment HO H with maximum absolute be the displacement displacement increment the first displacement 0 Hi the increment. rotation iteration. j t h and component Fig. 4.3.1). increments. rotation. increment Le t value Suppose and н 4-1--0 Hi

$$p_{d} = \left| \frac{\Delta r_{j}^{1+1}}{r_{j}^{1}} \right|$$
  $\rho_{r} = \left| \frac{\Delta r_{k}^{1+1}}{r_{k}^{1}} \right|$  (4.6)

Then the displacement ratio σ м М defined У У

σ Ħ the larger 0 ρ<sub>d</sub> and D H (4.7)

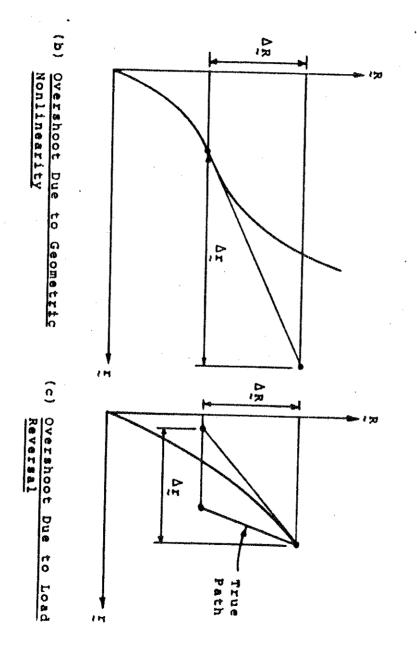
gence The tolerances displacement ratio as follows. σ is compared with three conver-

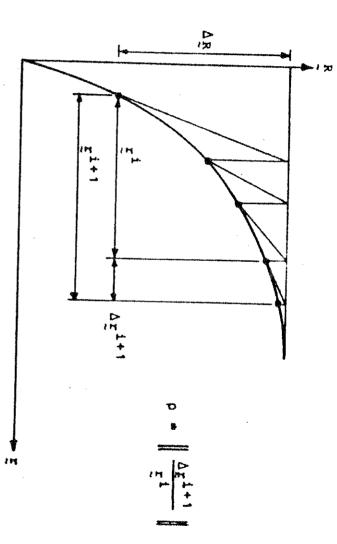
(2) (1) <u>u</u> р. Н rt Hi н H н њ ы М H Ô σ σ σ σ  $\mathbf{\sigma}$ (for (for (for v ł٨ v 1. ł٨ ۴۱ ...د س ц ц rt rt h rt changing stiffness) final load intermediate ů ₩1 ₩ បនខ proceed to next proceed to next time continue iteration continue iteration previously step) load formed steps) load step step. and triangularized

stiffness for next

iteration.







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Displacement

Ratio Tolerance

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$$\Delta r_i = \Delta r_i \times (\text{the smaller of } \left| \frac{t_d}{\Delta r_j} \right| \text{ and } \left| \frac{t_r}{\Delta r_k} \right|);$$
  
 $i = 1, 2, \dots, n$ 

If 
$$|\Delta r_{j}| > t_{d}$$
 and  $|\Delta r_{k}| > t_{r}$ , set

(3)

) If 
$$|\Delta r_j| \leq t_d$$
 and  $|\Delta r_k| > t_r$ , set  
 $\Delta r_i = \Delta r_i \times \left|\frac{t_r}{\Delta r_k}\right|$ ;  $i = 1, 2, \cdots, n$ 

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$$\Delta r_i = \Delta r_i \times \left| \frac{\Delta r_j}{\Delta r_j} \right|$$
;  $i = 1, 2, \cdots, n$ , where n number of degrees of freedom in the struct

$$\Delta r_i = \Delta r_i \times \left| \frac{\tau_d}{\Delta r_j} \right|$$
;  $i = 1, 2, \cdots, n$ , whe

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0 ц Ц increment +h displacement increment nonlinearities analysis placement rh 0 H crement the each displacement vector iteration are (Fig. Δrj, Δrk for and kth (Fig. 4.3.b) the 4.3.c), maximum allowed 0 current component has the provided.  $(t_d)$  and the rotation increment  $(t_r)$ load 1 H <u>២</u> ខ iteration. reversal the maximum Suppose maximum the displacement values jth rotation component of the

3 H h v с† Ь and  $|\Delta r_{\rm L}| \leq$ et. ۱ -ທ (†

н 0 tangent guard against overshoot which may occur in geometric nonlinear stiffness unfavorable situations method щ Ц О ц iterations. analysis with material 0 the 019 19

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step the Ъ iterations provided above erformed maximum number In <u>م</u> addition are ceiling for allowed 11 0 0 each stringent. ť ի. Մ O Hi load step м 0 Н the provided iterations intermediate convergence л 1. н. Н сt О ы. И Case limit allowed the load tolerances convergence the maximum number steps, for number the described and final of iterations tolerance ц т o р. 19load ħ

### \* **ω** Numeric 2 Examples

## 4.5.1 Time Dependent Analysis о ħ ţ0 Concrete Prism

d H considered and shrinkage Concrete Joint procedure shown m h tension erent 0 In order 11 reep load Fig. ы. Ю strain history loading **ب**و history بد وم \*\* դ ո գ assumed concrete assumed 11 0 4.4, 9 L demonstrate the 10, ages are and temperature history is analyzed with simple modulus linearly prism having t N đ and Ħ 0 0 20, given. is assumed to vary temperature specific elastic с<del>р</del> Ш time only . Four 30 ζ both in compression compliance dependent one and time numerical 91 (B degree †1 4 steps with Ħ given analysis <u>б</u> curves 0 ø time н data ወ Freedon HOH

G 7 ,t-T) . µ. "∎ M ⊶  $a_{i}(\tau) [1-e^{-10^{-1}}(t-\tau)$  \*\*1

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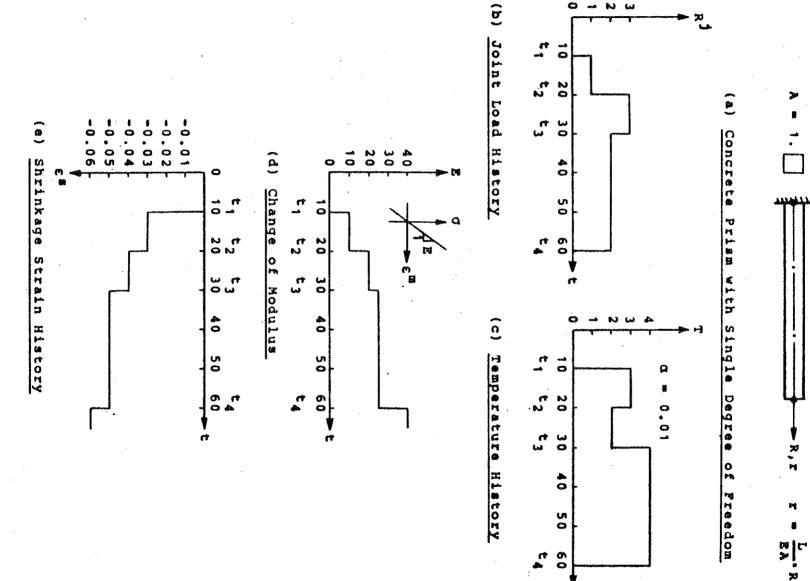
given

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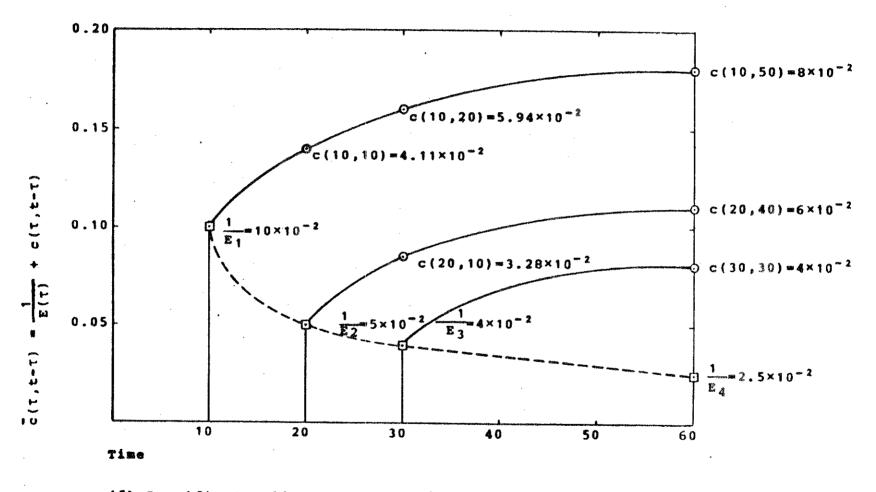
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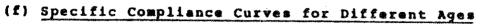
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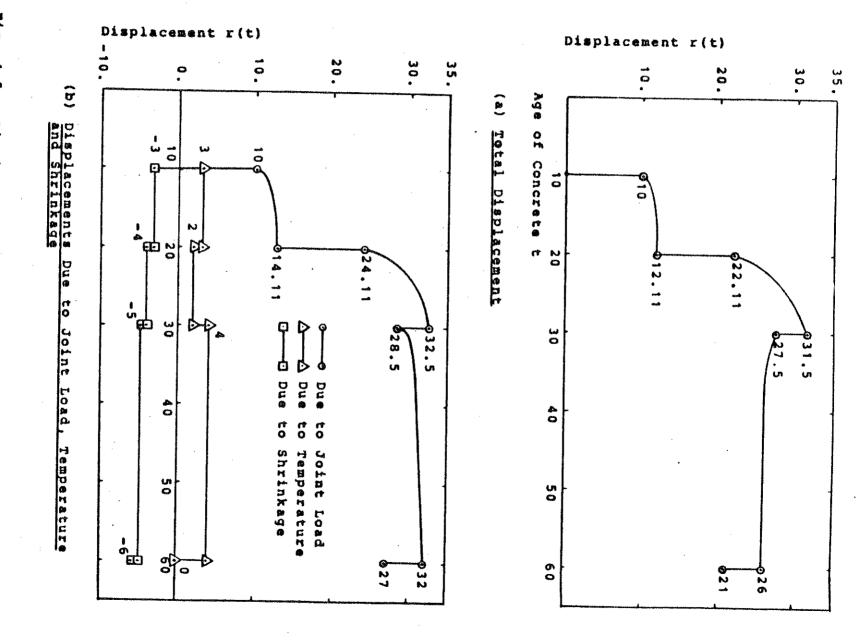
L=100.







₹ig. 4.5. Displacement History 0 . Concrete Prism



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F O F 11 4 would using evaluated H O T 4.44255 have loading each thi The The simple give Щ Д Ś × age time following sequence values 10-2 example Åq (3.32), the numerical creep त using Eq. step. , a<sub>i</sub>(30) same and used are (3.35) and r† these values result. ş.e., N 1 (3.26) assumed 3.22854 •• a<sub>i</sub>(10) 0 values (3.36) with rt Ö computations that are (3.28) directly × 10<sup>-2</sup>. Ņ gi rt 5.57296 a chosen such that the last Ħ ф(T) а N Creep × 9 T 0 ll 10-2 Ħ α ω time strains performed هد. ب instead ն։ rt which a<sub>i</sub>(20) each atep £ 0 are n 0 a n Ħ

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**n** displacement and the Calculate the incremental and strain. total values 0 ۲ħ the

<u>р</u>. Calculate t b e stress

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0 М (L/E<sub>1</sub>A) . Я Ņ 10. ••• ሮ **....** . r<sub>1</sub>/L Ņ õ х **1**0 1 N

ρ. q  $E_1(\varepsilon_1 - \varepsilon_1^{nm}) =$ 

(2) Analysis ри ct time step N , t N N O

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۵ د Ω. 0 Q, Ω, n υ, Δe3  $\Delta r_3$ ∆<sub>R3</sub> տ ա Q N т 4-D q Δ<sub>R</sub>nm  $\Delta \epsilon_3^{nm}$ ∆e3 ∆£c 3 ∆€2 ۵r<sub>2</sub>  $\Delta R_2$ Δε'nm  $\Delta R_2^{nm}$ m ო ่าต m (4) ω ωa Ň No ω 0 4 Ħ 1 . Ħ 1E H . N 1 Ņ • • m ii. a  $E_2(e_2-e_2^{nm})$ Ħ 8 Þ€ D ∆r<sub>3</sub>∕L ی دΩ 1 c (t 1 ო Analysis ω  $(L/E_3A)\Delta R_3$ m q m ∆Rj 2 + Analysis  $\Delta r_2/L =$ ო m  $(L/E_2A)\Delta R_2$  $E_3A(\Delta \epsilon_3^C)$ E2A(De2 ນັສ ສັ A 0 (E3-E3 Δe N ພິດ ិភ្ល Δe សធ NO -----0 ( tt (1/E 1 ωQ 1 NO U + + ິ ຄິດ en. ھبہ ت ∆R3nm + Q 1  $\Delta R_2^{nm}$ 11 ∆εз ω n N rt Δe đ ∆e3 t ⊳ m :4-t1) ~ ์ **ว** ธ 11 5.39 12.11 ់ក ធ N N + × ն 11 р rt m rt + NO lŧ œ Ħ 10 ŝ स्र μ Se 30 Ħ Ħ . υ 9 ∆es 2 + N H + time ىبە • 2. υī tine Ľ + ∆e × თ • 1.3475 ∆et 2 ----12.11 N • 7.11 \*\* + × X + φ N ---ن و + ×. 0 Δσ<sub>2</sub>c(t \*\* ٠ i an 422 ŧ æ 10-2 Þq ·2)  $\Delta \sigma_2 c(t_2, t_4 - t_2)$ w **U**I Δσ<sub>2</sub> step Δσ<sub>3</sub>  $\Delta \varepsilon_{3}^{t}$ dets  $\Delta e_2^t$ ŧ + + D € ົ ດ ~• N × х 1 × ∆e3 ⊳ e N ----NA 10-2 ;(t<sub>3</sub>, κ ω 10-2 -9 Ħ l **N**ິຍ 4 N ы υ. N θ ω ω L Ħ ٦, ۲, ່ດ ພ N H 1 р N . # H ო N х I. n Au De3 rt N 2.3475 De 0.422 Ħ t 4 H 2 i i ....**A** ł rt, -1 -N --Ŧ ta ۰ سم سم rt ω. °.‡ M × đ m Ľ, a v Ħ ں و N + . q . m N --0 **.....** Δr<sub>3</sub> 60. 30. + N x N •• 1 1 H 11 × \*\* N ----D H N 10-2 ∆RJ 2 ч N х × ∆ ₽ 3 10-2 ŧ m × N • <u></u> − 6 D C C 10-2 10 ŵ 1 S N A х 27 H H х Ħ . 22 . Մ N • 27 2 ŧ -0 1 Ň <sub>σ</sub> × 0 х 1 o

ø ф. рн Н ð 9 and ġ, Ъре et 1 4.7, ria truss properties among consists which only like 0 m three concrete the 0 middle н Ф ments, ►. pa. 0 element • () () μ ct shown cracks has 15 nonlin-15 Fig.

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Нŋ using computed 5 ñ 1 1 1 1 1 1 compute the comput according to ሮ ተ н ø program (3.32), н analysis developed the (3.35) the procedure and creep for (3.36) strain this developed study, increment i n RCFRAME. section ∆e° n ۱۲. ۵ ເມ • ω

j u F1g Hbe ۵ • results СЛ are checked with the solution obtained Уq

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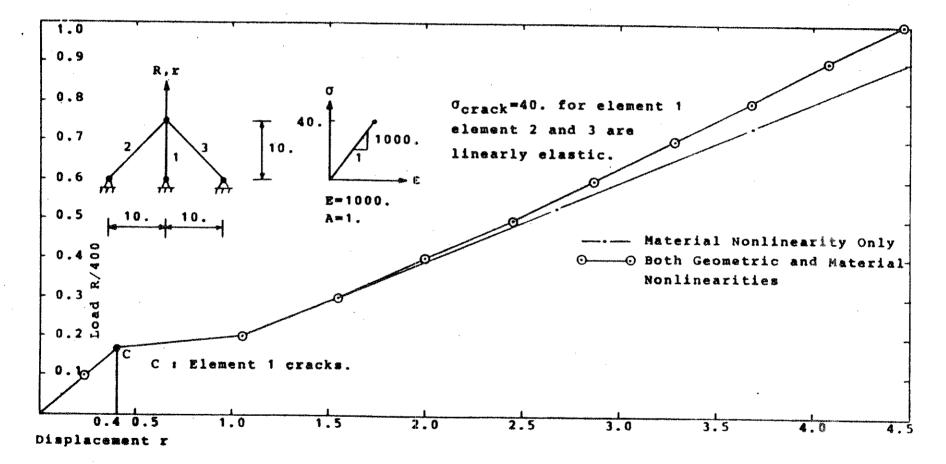
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same the elastically tension stress-strain diagram. modulus and both yields с С the 15 and crushes compression middle element, The outer two elements in compression and tension. but they behave a N shown have linearly н. Э the

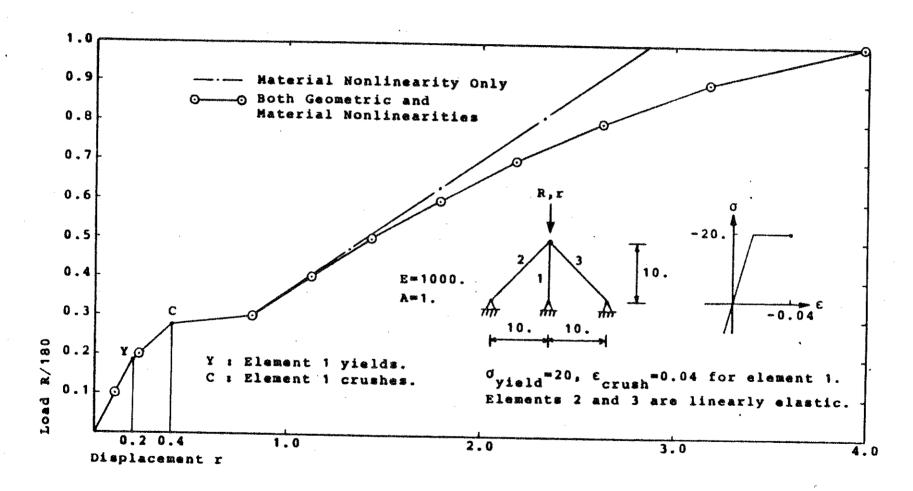
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geometric μ. subjected <u>ن</u>م cracked 11 Fig. nonlinearity. rt Ö we notice 4.6 tension the t b e н. Ю load-deflection curve plotted. stiffening After 0 Fh the the 0 truss due middle the truss element t 0

due yields pression is 0 Load-deflection curve and geometric crushes, plotted in Fig. 4.7. nonlinearity. the structure 0 the can truss After 6 0 the middle subjected seen rt O 00 rt Q element softening 00B-



#### Fig. 4.6. <u>A Truss Subjected to Tension</u>



#### Fig. 4.7. A Truss Subjected to Compression

# REINFORCED CONCRETE FRAMES

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## 5.1 General Remarks

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method based ወ calculation quati 01 Detai ons the led evaluati 0 displacement descriptions internal g 0 forces tangent formulation for the wi11 stiffness derivation e D 0 1h given the matrix finite ų L 0 H this Ø and quilibrium • chapter lement the

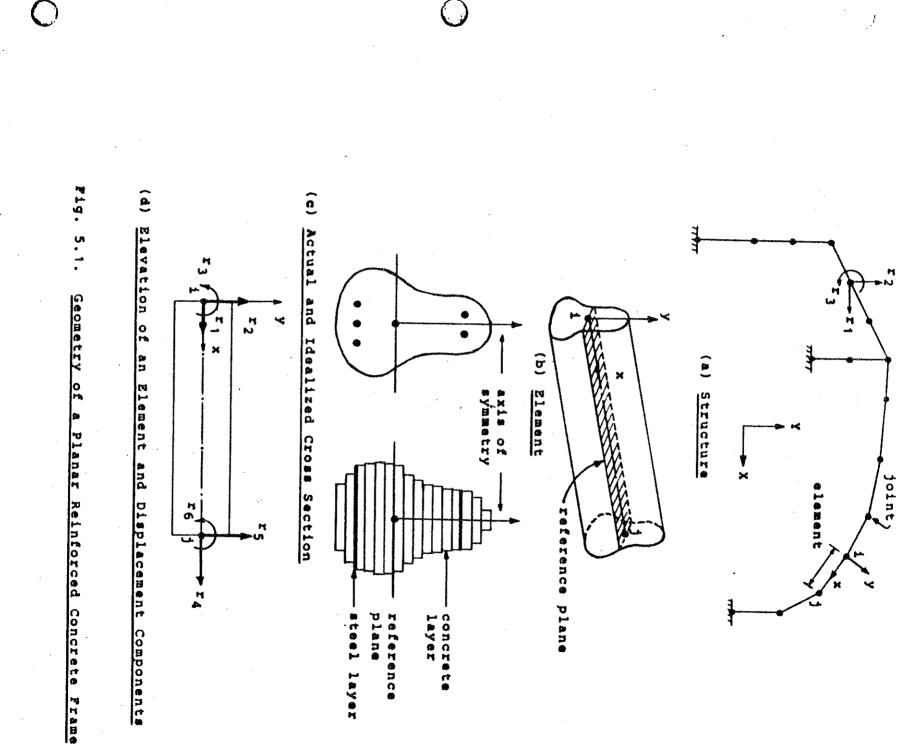
### ហ • N Def initions and Assumptions Regarding Geomet 7 and

## Deformation

tt e . س 'n H O. shown onnected ¥ typical ц. Т Fig ЪУ planar ٠ joints 5.1. reinforced The structure 000 o consis H 0 rt (D) ħ 61 (A amed 0 H ø () lements et ruc tur jun

n г† µл. H ö 5 ິ ທ which Hach section element has may an axis differ μ. (A assumed 0 1-1h element symmetry. с† О have by element. But ()ø prismatic the shape Cross o th the 09 (P n 1

Then axi and follows. ٥, u. t 5 ٠ Ho c and n Joint a L axis the te e t 00 ordinate S T X 8 connecting ş., the թ. 00 two perpendicu the G joints origin × the Ś н о т two 121 р ct 0 Hi each the rt 0 joints the the ends element local × μ. 0 Fh ÷ axi **ب**نا. 0 9 oordinat 00 defines are H 5 elemen defi the Ø t b e 11 n e d plane system տ Ծ × ດ ເກ . سو



rt H 4 ц. Ц æ O, 0 p... H rence 05 ā a x i s d e tрe the with coincides plane ትክ የተ × ame axis and is t ne 0 Hij define centroidal the with n element the also the axi 4 axis perpendicular ы Х ր. Տ CO Fr. 0 Hi (A) 0 defined . t n e symmetry The frame × р С axi rt 0 the ø 0 H 'n x-y lement ne the plane Ð plane. p, 10 L 0105 ٠ contain-The Ø 0 0 0 0 0 The ц. Д ref-1

سر th. 0 rom ауе н Ø, rt н ø the tri ր. Տ and P ö 5 reference defined element rein for by cing յեր. ՄՈ plane պ. Դի Ծ divide steel Cross ρ. layers. into 0 0 0 μ. Qe onal disc The area rete geometry and numb the ወ 0 Ħ н o distance each Ξ. Ô 051

8 Y S the +h 100 H 0 0 TT. et H μ. 63 d on 0 ц. Н nal Each the global degrees The joint displacements ងឧទ 0 coordinate system freedom three degrees and one 0 each О Њ joint rotational 0 H freedom, the сал local н. Ю 0 D degree de fined coordinate させつ 0 trans-

and b e μ. 0 structure The common global FOF are coordinate 01 (1) (1) all elements. up and solved system Equilibrium equations × in this к ۲. ۵ fixed coordinate 1 n space, system Hi O

ture and Ω each 1 coordinate urre the 0 P element. IJ ۲IJ rt lemen forms internal 0 ñ system rt ations σ roperties However forces 0 Hi are the continuously • such the are formed two origin joints 0# () the and changing in local which vary as element the directi according coordinates stiffness the 05 0 . tt matrix struc н 0 н this the

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IE Ħ <(1-3p<sup>2</sup>+2p<sup>3</sup>),(3p<sup>2</sup>-2p<sup>3</sup>),L(p-2p<sup>2</sup>+p<sup>3</sup>),L(-p<sup>2</sup>+p<sup>3</sup>)> ł (5.6)

$$\frac{\Phi}{\Phi} = \langle (1-p), p \rangle \quad (5.4)$$

$$\nabla (\mathbf{x}) = \frac{\Psi}{\Phi} \left\{ \begin{array}{c} \nabla \\ \Theta \\ \Theta \end{array} \right\} \quad (5.5)$$

u<sub>0</sub>(x) = Θ-N ^ ŀЭ 20 U V

(5.3)

С Ф ment Let <u>p</u> linear can write u<sub>0</sub>(x) and of any point variation v (x) along the o F b e u<sub>0</sub>(x) the x-displacement frame axis respectively. and cubic variation and the of v(x), y-displace-Assume then

ъ Ħ ×/Ľ (5.2)

the position along P non-dimensional the axis parameter 0 the ΰ ۳-۵ frame defined which element 0# (4 represents follows.

$$\tilde{u} = \begin{cases} u_1 \\ u_2 \end{cases} ; \tilde{v} = \begin{cases} v_1 \\ v_2 \end{cases} ; \tilde{\theta} = \begin{cases} \theta_1 \\ \theta_2 \end{cases} ; \tilde{z} = \begin{cases} \tilde{v} \\ \tilde{\theta}_2 \end{cases} ; \tilde{z} = \begin{cases} \tilde{v} \\ \tilde{\theta}_2 \end{cases}$$
(5.1)

14 ц. rt. oint ations respectively. displacements are represented рÀ components vectors ្ក ंद and

$$\tilde{u} = \left\{ \begin{array}{c} u_1 \\ \vdots \end{array} \right\} ; \quad \tilde{v} = \left\{ \begin{array}{c} v_1 \\ \vdots \end{array} \right\} ; \quad \tilde{\theta} = \left\{ \begin{array}{c} \theta_1 \\ \theta_1 \end{array} \right\} ; \quad \tilde{r} = \left\{ \begin{array}{c} u \\ \tilde{v} \end{array} \right\}$$
(5.1)

coordinate rees 0 Fh 0 the system. freedom two end joints, and all are defined x-displacements, y-displacements ц. Ц Fig. ហ • 2.a in i Li Li Li 0 local the and H 0 -

à and Derivation Displacement Material components Nonlinearities Equilibrium 0 f Equations Including ω and frame element Non-mechanical having six Geometric Strains

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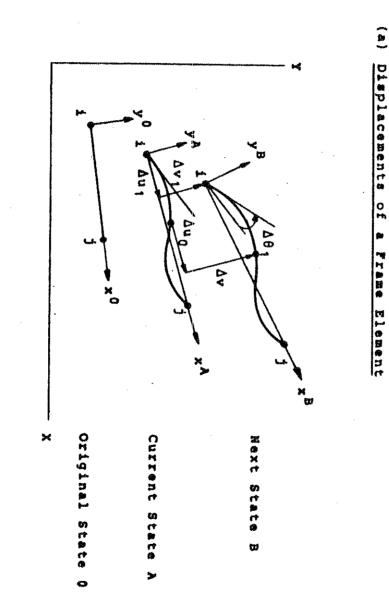
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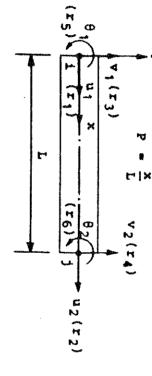
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placement perfectly Concrete bonded field and 0 m together. the the reinforcing steel frame This element assumption continuous. are makes assumed t b e rt Ö - stp 0 D



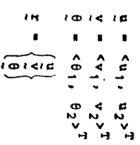
## (d) Frame Element 1 1 Various States o n Deformation





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р. Н spectively. which I-@and ŀe are shape functions н 0 н u<sub>0</sub>(x) and √ ( x ) 181

frame xpress Let u(x,y) be the x-displacement element. u(x,y) in terms Then by the 0 Hi joint plane displacements section 0 H any point assumption we can () () () follows н. р 0 1 1 0

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$$u(x,y) = u_0(x) - y\frac{dv(x)}{dx} = \frac{\phi u}{2} - y\frac{\psi}{2}, x \left\{ \frac{v}{\theta} \right\}$$
(5.7)

u(x,y) and v(x) may be expressed 11 terms 0 ₹<u>₩</u>

u(x,y) = <\$,-y\$ > √(x) = ×0,4× r 2 15 (5.9) (5.8)

 $A_{x_i}$  al strain  $\varepsilon(x, y)$  is defined by (102)

$$\varepsilon(x,y) = \frac{du(x,y)}{dx} + \frac{1}{2} \left( \frac{dv(x)}{dx} \right)^2$$
 (5.10)

ment 11 which effect. the second term represents the nonlinear displace-

¥ (1) equations which Åt Å ordinates (A deformed state. states formation increments  $\Delta u$  and  $\Delta v$ . rent tate. note that the origin and the direction of the local cochanging. state A H 0 Hh Fig. 5.2.b a frame And state B represents deformation. х,у, with Total, incremental and the length of are State the valid at displacement A represents the current いたみため element is shown in the 0 the next state from the currepresents As the frame and the current increments element tangential state the are ۵ ۲ element deforms, its various ≫ original deformed equilibrium and the will be decontinuous-ជក + വര ര 1

r coordinates, and loads rent veloped lement state and volume internal forces All A, so that joint the integrations state variables 00 M 00 displacements, are performed over referred are ref rt O erred t he deformati current 11 0 t De the on s current local 041-

from 10) total values with the ormations the the Consider following current state Δu, Δv a finite expressions and the incremental A, with corresponding change strain  $\Delta \epsilon$ . can i n the e D values derived by joint From н д displacem changes (5.8) replacing the ents rt 0 ц. 0. 0. <del>.</del> ა ך א≀

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۰ô ψ, > Δ<u>r</u> -,x <sup>×</sup> (5.14)

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state A represented by Eq. (5.15) may be relationship at the rewritten

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(5.17)

(5.16)

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ta 'n 11099905 which, change сл Сл the đ joint (α+Δα) displacements and the joint loads change Ъy required ∆r, the ц ц

 $d\overline{z}^{T}(\underline{R}^{j}+\Delta \underline{R}^{j}) =$  $\int_V d\overline{\epsilon} (\sigma + \Delta \sigma) dv$ (5.23)

The virtual work equations ր 17 the state W can 0 D written

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The virtual work equations рі ct the state Þ can e D ¥ r r c† 1 0 1 1 0

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ing ÷ч maintain mn T ים הים equations (5.22) into the equilibrium change.to ն t 11 17 0 Eq. (5.23) state ω we obtain the (R<sup>j</sup>+ΔR<sup>j</sup>). total вy substitutequilib-

$$R^{j} + \Delta_{\tilde{R}}^{j} = \int_{V} (\bar{B}^{T} + c^{T} c \Delta_{\tilde{L}}) (\sigma + \Delta \sigma) dv$$
 (5.24)

and a r e neglecting the higher then The obtained incremental уq subtracting equilibrium order term equations ម ភ្លេ • <sup>J</sup>vc<sup>T</sup>Δσcdv·Δ<sub>ž</sub>. (5.21) from Eq. at the state (5.24)Þ

$$\Delta \tilde{R}^{j} = \int_{V} \tilde{B}^{T} \Delta \sigma dV + \int_{V} \tilde{c}^{T} \sigma \tilde{c} dV \cdot \Delta \tilde{r}$$
(5.25)

da. Ô from 1010 The ы Д The and tangential stress-strain relationship (5.25) by replacing  $\Delta \underline{r}$  by  $d\underline{r}$ ,  $\Delta \underline{R}^{j}$  by  $d\underline{R}^{j}$ tangential equilibrium equations the reinforcing steel can be written can be obtained for and  $\Delta\sigma$  by both con-

$$d\sigma = E_t de^m = E_t (de - de^{nm})$$
 (5.26)

E G L Cal defined 6 J e where strain respectively, and  $\mathbf{E}_{t}$  is the mechanical strain, (5.26) de<sup>m</sup> н. П ÷ **ሲ** ም chapter and de<sup>nm</sup> N • the total strain and the non-mechani-0 7 0 By substituting the infinitesimal increments Eq. (5.19) for tangent modulus de into Ö Hi

$$d\sigma = E_t \underline{B} d\underline{r} - E_t de^{nm}$$
 (5.27)

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the สุทธ gives ŵ incremental titution of us the following tangential equilibrium equations operator Eq. (5.27) Þ by the into Eq. differential (5.25), arter operator replacing Ď ы ст

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ط ۲<sub>۳</sub>۳ #  $(f_{vB}^{T}E_{tB}dv+f_{vc}^{T}\sigma_{c}dv)\cdot dr$ I ∫v≞<sup>T</sup>Etde<sup>nm</sup>dv (5.28)

By defining the following terms

Kt = Ke + Kg	≚g = √v⊆ <sup>T</sup> σ⊆dV	re = fv <sup>br</sup> et <sup>b</sup> dv	$dR = dR^{\dagger} + dR^{nm}$	d <sub>R</sub> nm = $\int_{V_{a}}^{B} T_{E} t_{d} e^{nm} dv$	
(5.33)	(5.32)	(5.31)	. (5,30)	(5.29)	

we can rewrite the Eq. (5.28)

dR = Kedr

(5.34)

rial 0 geometric nes s cause these strain-displacement relationship nonlinearity consists tor due equations the או יי properties. This stiffnesses the ø to non-mechanical lement 0 which are valid The nonlinearity since integrations is the the and the geometric elastic stiffness elastic desired d,Rum are dependent are 50 14atiffness form strains. the equivalent load increment vecн 0 1 performed ų. the current geometry of the stiffness on the current originates Ke represents in Eq. (5.10). Xe and the The tangent stiffness over tangential n M G the from represents the geometric the material current geometry beequilibrium the But both of and matenonlinear volume 8 C 1 5 5 5 -אן רז

the and r† Ø frame × <u>.</u>., train 9 only, while 4 values ц. р Note ወ since state. lement both that 0 the value × ات را 0 0 the ן שו and Thus well р с† tangent н 0 4 н. ст the directions. þ 04 () 0 F յտ. Ծ constant matrix, mid-length of ात भ through its necessary modulus varies 11 17 However, along t 0 ч s depth the perform the integra-0 1 00 ¢۵ the frame function according յե. տ ₽. Hi length × e QJ element function 07 (7) ŝ of both ume 0 H tt 0 (5.38) the the that rep-0 H ×

ж Ф √v<sup>B</sup>TEtBdV Š -увьесва Bartea Bartea y<sup>2</sup>BbetBb -yBartBb 4V = , N N N N N dd X i X a D

-100 F 7 0 1 H ~⊎,×× > т Д (5.31)(5,37)

Then

p,  $= \frac{2}{L} \left( \frac{3}{L} \left( -1 + 2p \right), \frac{3}{L} \left( 1 - 2p \right), \left( -2 + 3p \right), \left( -1 + 3p \right) \right)$ 

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(5.36)

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1 n resent ២ ភ្ន • (5.38) can be the average value along separated its length, as follows. the integrations

173 90 90 Ħ -#  $\int_{\mathbf{V}_{a}} \mathbf{E}_{b} \mathbf{E}_{b} \mathbf{d} \mathbf{V} = \int_{\mathbf{V}_{b}} \mathbf{E}_{b} \mathbf{d} \mathbf{A} \cdot \int_{\mathbf{V}_{b}} \mathbf{E}_{b} \mathbf{d} \mathbf{A} \cdot \mathbf$  $\underline{\mathbf{x}}_{\mathbf{b}a}^{\mathbf{T}} = \int_{\mathbf{V}} -\mathbf{y} \underline{\mathbf{B}}_{a}^{\mathbf{T}} \mathbf{\mathbf{t}}_{\underline{\mathbf{b}}b} d\mathbf{V} = -\int_{\mathbf{V}} \mathbf{E}_{\mathbf{t}} \mathbf{y} d\mathbf{A} \cdot \int_{\mathbf{V}} \mathbf{\mathbf{b}}_{a} \mathbf{\mathbf{t}}_{b} d\mathbf{V} = -\int_{\mathbf{V}} \mathbf{E}_{\mathbf{t}} \mathbf{y} d\mathbf{A} \cdot \mathbf{f}_{b}$ BTBadx B<sup>T</sup>Bbdx (5.40) (5.39)

494 X Ħ  $\int_{V} y^{2} \frac{B}{b} E_{t} \frac{B}{b} \frac{d}{d} V = \int_{A} E_{t} y^{2} \frac{d}{d} A \cdot \int_{O} \frac{B}{b} \frac{B}{b} \frac{B}{b} \frac{d}{d} x$ (5.41)

well compensates the increased computation time ŝ librium state. creased, number nonlinear equilibrium equations as discussed in trix Note avings is not that the 1 5 the computation time due to this approximation a necessary requirement exact evaluation of the tangent of iterations required to for the solution of the arrive stiffness for the inchapter р р the equima -4

the frame The first integrals element рÀ a layer are evaluated integration 94 67 a S the mid-length follows. 0

(m) m ≻ . JAEtdA = L EciAci + L EsiAsi (5.42)

S  $-f_{A}E_{t}ydA =$ "c -Σ EciyciAci -Σ EsiysiAsi i=1 EciyciAci - 1=1 EsiysiAsi (5.43)

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Ħ JAEty<sup>2</sup>dA  $\sum_{i=1}^{n_c} E_{ci} y_{ci}^2 A_{ci} + \sum_{i=1}^{n_s} E_{si} y_{si}^2 A_{si}$ (5.44)

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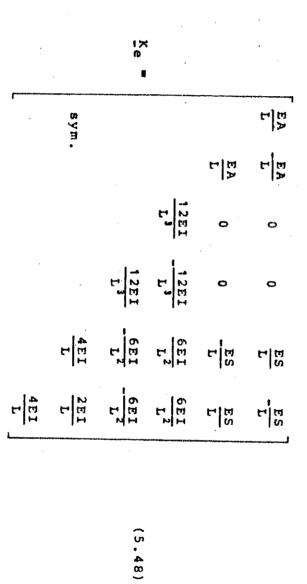
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respectively, and the subscripts

where ወ н. 8 the axi al force 0 Hi the frame element. ЯÂ inte-

$$\underline{\mathbf{K}}_{g} = \int_{\mathbf{V}} \underline{\mathbf{C}}^{\mathrm{T}} \sigma \underline{\mathbf{C}} d\mathbf{V} = \int_{\mathbf{A}} \sigma d\mathbf{A} \cdot \int_{\mathbf{C}} \underline{\mathbf{C}}^{\mathrm{T}} \underline{\mathbf{C}} d\mathbf{X} = \mathbf{p} \int_{\mathbf{O}} \underline{\mathbf{C}}^{\mathrm{T}} \underline{\mathbf{C}} d\mathbf{X} \qquad (5.49)$$

fu ft the mid-length geometric 0 H stiffness the frame ۲X Q element can ь С р S evaluated similarly follows



follows combining Eqs. (5.38) rt 0 (5.47).

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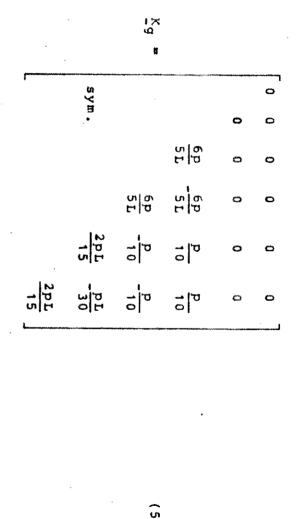
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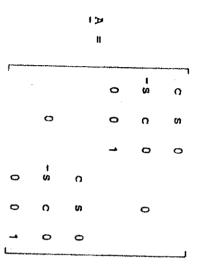
the Fig bal ЪУ 0 Ø ١0 nent ness tiffness transformed from the local element adding ţ, coordinates. following matrix υı • The shown 2.8. element matrix, ፣ኦጎ በ the in Fig. and Then equation. numbering 1X 9 tangent element the FOR FOR 5.1.0 the transformation 1 n stiffness order թ. Ծ system tangent assemblage used ő HON N instead of stiffness form matrix 0 m the can coordinates the the displacement Ծ Թ ц х ц structure structure matrices performed 14 |--せりぬせ then shown in rt 0 the gloobtained have tangent compostiffwith с† 0

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stiffness μ. Ω e D assembled rt Ò the method global coordinates, in <u>p</u>u (1, 2). standard manner tangent t D e utilized structure stiffnesses. ц ц tangent the are dire transformstiffness 0

#### ທ • ຫ Calculation 0 Strains and Stresses

whi (A ø lation 0 T 0 elimination study dure rt p lement 0 t n solved discussed FOR displacement increments variables (Ja 0 Fi ա. տ symmetric each the for outlined procedure strain iteration global displacement in should chapt. banded and н ա. տ ъ Сe н. Э <u>م</u> the the used. equation referred the tangential equilibrium equations stress following D i H course The are solver đ increments. ы rt procedure not the 0 Hi description any utilizing added the current point solution н оr yet н он μ. 5 state the all Gauss the this calcuprocethe Ain frame μ. ងភ

Trans form global displacement increments ∆r<sup>G</sup> đ

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r† local ransformation displacement بر م performed increments by ∆ ז∶ the for following each element. equation. The

Ħ ΑΔr<sup>G</sup> (5.53)

calculated where (2) the Strain transformation matrix ъ ъ Ч increment (5.16). Total strain e D € ល ក I Þ any point was defined is then obtained i n by Eq. the element (5.52). ₩.

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cal steel due to shrinkage, non-mechanical strain ɛ<sup>nm</sup> strain e<sup>nm</sup> (3)... the Mechanical strain aging and temperature effect is due to the combined effects of temperature from total strain E. ел is calculated changes changes нон for concrete, and Åq reinforcing 0 subtracting Non-mechanicreep,

used. used, given in chapter 2. For concrete, Eqs. (2.30) to (2.33) are (4) and for Stress reinforcing steel, q is calculated Eq**s**. by the nonlinear (2.34) to (2.36) d-em 0 X 0 curve

quadrature н. 0 õ. i n performed The the computation of strains and stresses described next points along for each concrete section. the length of the element and steel layer p) ct ф Ю ω Gaussian explainabove

თ • თ Calculation 0 14 Internal **Resisting Loads** and the ø

loads Equivalent Internal required ЪУ resisting to hold the structure total equilibrium Loads Due to Non-mechanical Strains loads ۲<sup>۳</sup>-Eq. which in equilibrium, (5.21) for each can D 0 defined element. н. (2) 01 51 calthe

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о њ non-mechanical Equivalent load strain increments Δε<sup>nm</sup> are  $\Delta \mathbb{R}^{n,m}$ calculated due rt 0 the by ក ភ្ល • increments (5.29).

∆<sub>R</sub>nm Ħ √v<sup>B</sup>T; E<sub>t</sub>∆e<sup>nm</sup>dv (5.55)

tion this tion Gaussian ternal joint comparison have Hi O H ф 0 reason Unlike b e quadrature the between calculated as accurately both tangent iterative loads ۶<u>۳</u>4 form the the and stiffnesses, (95,96) combined with the nonlinear internal ∆Ŗnm basis 8 r e resisting internal evaluated analysis of the equilibrium ն Տ possible procedure loads resisting Å Å layer integra-¢۵ 3-point and because load the correc-可 O F e X I the

the рі () which tion follows volume f(x) which is dependent Each r F dependent component 0 the element. 05 of the vector poth × The and оп ж integration Y, يد: ۱۳۰ only and ő 0 M 6 D Δ<sub>R</sub>nm integrated pø can function g(x,y) contains 0 performed over p, func-

050  $f(x) \int_A g(x, y) dAdx$ N NH ل f (p) المع (p,y) dAdp o ົິ 56)

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NH

 $\sum_{k=1}^{3} w_k f(p_k) h(p_k)$ 

Խ 2 weights where 0.112701665379258, three ×× are Gaussian ¥ 1 H integration ,6/8 ъ С ¥2 ł 0.887298334620742 H ¥ u points 5/9. q ۲ 8 F 6 • and ď

the

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0.5,

(5.57)

h(pk)

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ر Ad (b<sup>k</sup> 'A) d y) d y

-, oad vector  $\Delta \tilde{R}^{nm}$ Internal resisting 1% 0 M each element load vector are transformed 177 and the equivalent († 0 the

O where n<sub>c</sub> in steel is the number of layers. concrete layers, Ħ 68 р. 0 the number

 $\int_{A} y \sigma dA = \sum_{i=1}^{n} y_{ci} \sigma_{ci}^{A} c_{i} + \sum_{i=1}^{n} y_{si} \sigma_{si}^{A} s_{i}$ 

. ۲ ЪУ the layer integration For example, for each Gaussian integration point

The function h(p<sub>k</sub>) defined ЪУ Eq. (5.57) р. Ф.

evaluated

		L	
wu <sup>3</sup> Ų <sup>3</sup> 3	Q	-+	s 3
yE <sub>t</sub> ∆€ <sup>nm</sup>	уσ	$\frac{2}{L}(1-3p)$	s2
yE <sub>t</sub> ∆e <sup>nm</sup>	yα	$\frac{2}{L}(2-3p)$	s 1
for $\Delta R^{nm}$	for R <sup>1</sup>		
g(p,y)	1) ɓ	f (n)	'n

£(p) are <del>بر</del> ≀ + ው በተ forces components н. Э 9 7 Q strains shown load vector Fig. joint or the only computed by the equilibrium requirements. and g(p,y) for the calculation of the sţ, 5.3.5. three j and S<sub>3</sub> is the axial force. equivalent load vector  $\Delta \tilde{R}^{nm}$ s 2 need form and in Fig. independent S<sub>1</sub> is the moment at joint ő a self equilibrating system S<sub>3</sub> are 0 0 5.3.a. calculated, and the tabulated internal force Since these components of the below. due to non-mechanical Thus only these three 348. 14 other component three internal s 2 of forces there The components is the moment functions Ś ດ ທ shown

106

X H S

components

0

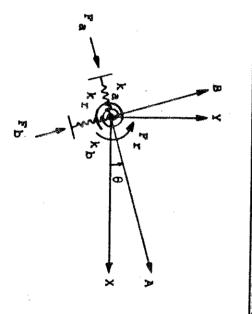
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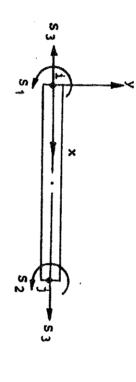
vector

Fig. U1 Support Springs and Reactions

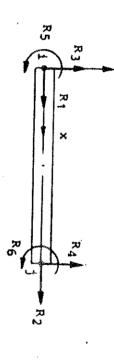


••• ••• Internal Loads 0 2 Frame Element

# (b) Three Independent Internal Forces



â Components 0 the Element Load Vector



I⊅ H global defined coordinates in Eq. (5.52), and assembled ЪÀ multiplying 4 1 1 0 transformation но г the structure matrix

#### -1 Treatment 0 Ξ'n, Boundary Conditions and Calculation of

### Reactions

۰UN

4 and μ. £Ť means 'n ided hogonal rotated ω Spring Boundary 0 form њ он directions support each ЪЛ μ stiffnesses rectangular conditions an angle support springs. ¥ and Φ α S × ρ. , ጨ ተገ from Cartesian W shown Two translational and <del>بر</del> م the the global coordinate system. and н. Э a rotational anbbort , ж н coordinate Fig. associated with 0) 11 0) ა. • 4 • ហ spring are springs pecified system which Spring 1 n axes А А these 0101 0 1 1 )>

t 0 direction, zero tions three that value ն։ rt springs direction the н. Ю μ support. large are specified ۲. ۵ specified value specified, and FOF њ 0 н 0 Hi φ đ the spring 2670 simulate spring displacement stiffness н 0 1 stiffness the ρ free displacement, boundary condicorresponding in the specific

2 ŵ coordinates Support spring Ω N follows stiffness matrix 173 04 may b, D written н. Э

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(5.58)

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where  $c = \cos \theta$  and  $s = \sin \theta$ 

1 13 rt 0 solve ~ 173 0 0 ດ ບ for **ק** ק for each 1 the r'y T displacements support a re then ... Մ calculated added р ct each nt O the by the joint. structure equation The rea sti ction H H 2 ወ S n v

₹ H KST

(5.61)

L.

**O** in oordinates which 1 H ե. տ the displacement Vec tor а ct the support н. Э A - B

load internal resisting (4.5), vector In the calculating support <sup>۲</sup>۳. does Load reactions not the include vector unbalanced have ۳1 ۳ the rt 0 since load reactions be subtracted vector the external joint <sup>i</sup>Ru ЪУ from Б Д the

5.8 Summary

and 0 H HOH loads, procedure rt reactions 50 planar frames Based equilibrium the ő equivalent 95 compute ,⊷. ניז the described described nonlinear equations, strains, loads due i n in chapter time this stresses, internal tangent с† О dependent non-mechanical chapter stiffness 4, detailed analysis matríx resisting S rt H derivation procedure a L รนา and the

the equ **D**# Ø rt ions Frects Total, including 0 incremental non-mechanical material and tangential and strains geometric 07 H 17 17 forms developed nonlineariti 0 Hi equili bas brium e S S n D, оŋ and

th. n moti 17 o ö ጋ በ H. in the 05 isting "Updated current The 0 expression for the Ləgrangian" elastic geometry and and formulation geometric material tangential stiffness components, н О Ч properties the description which ы. Ю derived. matrix, ы. М 0 m valid

ove h Ô o 4 n e transformation teria ö ormation ₽h ordinates ወ M ach integration the -Numeri properties element cur matrix . cal ۲. ۵ rent 0 performed evaluation of بر 9 over for length the 0 discussed. each concrete each element. concrete tangent 0 using the the stiffness and current The element tangent steel and integration displacement steel layer. using matrix layers stiffness the rt 0 0 1--նյ rt current the the performed matrix by trans The global center ma -

۳ ۳ ship and computed crements nonputed relationship eration. length բ. ശ mechanical steel Computation ъ С obtained 0 Fh ∆enm Уq accumulating the each layer be the from joint displacement |---64 for Åq strain e<sup>nm</sup> element currently valid stress-strain computed by a rt 0 subtracting each time step. w strains and Gaussian is discussed. ₩. (0 strain 0 computed e سر nonlinear strain-displacement quadrature stresses for increments from E. Total increments ЪУ Total strain mechanical accumulating points Stress each Þe (σ-ε<sup>m</sup>) ∆r. along н 0 Н q concrete m each p... strain is com-(A relation-Total the the then н rt I in-

thr ture non-mechanical ough along Internal the 1100 depth resisting length loads 0 14 0# 17 0 1 1 0 0 element loads evaluated the element and and the уq ω point μ equivalent layer Gaussian integration loads quadra due с† С† L

discussed calculation Finally 0 the treatment ctions уq 0 H providing support springs boundary conditions and are the

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. PRESTRESSED CONCRETE FRAMES

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# 6.1 General Remarks

ened σ ing while Ω ation, tensioning tures н before rt an stressed onded ed 5 oncrete ø ρ. steel is rt Ö σ ש concrete, н Ф ้ ผ Depending the the the post-tensioned and unbonded t n e stre rt i et and concrete prestressing prestress ወ operation. concrete concrete ssing nsioned grouted the and 01 prestressing steel structures the anchored against structure structures. р. СЛ ທ ມາ after 0 H structures method steel is tensioned against And depending transferred gradually placed, and the р. И ungrouted after р. ft tensioned Ω • has set are 0 Hi steel. applying In pre-tensioned are classified ₩. rt against on whether the by the bond further ۲n prestress immediately 6 1 2 1 2 post-tensioned struct ne tensioning into some ct O prestre classified the ير در between the structures preabutmen the hardafter prestress transfer-(A) (A) concrete tensioned operpreinto rt the ł

-1 H C r e Ъ E D еŋ havior pervariation of axa ous Ø ō н ans Ĥ m 1 Ъ rt 0 due 9 9 rt ø 5 Чe 1 O T stages of loading Ph. and ወ 1 Þ it ne 0 Ha the н tensioned с† 0 the 0 H due the prestressed effective amount the elastic transfer prestressing analysis the stress с† 0 relaxation the structures 0 m n 0 m reep concrete is an important shortening of prestress 1 1 prestressed 0 steel and the 0 prestressing the shrinkage and prestress prestressing steel during structures prestress due the concrete concrete 0 factor since the ወ the 5 5 7 8 7 8 0 steel acting 1th loss 1-9 0 t s concrete shrinkage largely structures \*\* 0 takes place on them and ۵ ۲۱ load ÷ the after the depend-0 history trans-000the varcontbe e I

Fig н frames egarding the . 6.1.a.  $\geq$ given typical Ľ n ۲IJ geometry planar chapter addition prestressed and U 11 0 the deformation the following definitions concrete 0 H definiti reinforced frame and .០កន assumptions <del>رم</del>ا ۱۹۰ and shown concrete in ч. Э

## Defini and Assumptions Regarding Geometry

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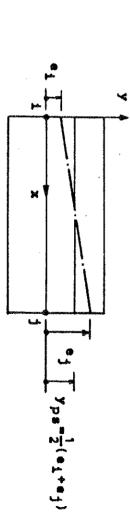
ture ι Hη r† 5 procedure prestressing steel. O material ъ, prestressed men temperature reinforcing tory rames ili H reep, one employed with \*\* only (A 'n ¥ and present Ħ are shrinkage and complate internal this nonlinearities those temperature developed discussed history, concrete steel study aim is ۲. ۲ features analysis forces, prestressed some modifications and previously 94 C† aging frames The nonlinear history. t be any stresses and distinct which includes both taken prestressing steel of concrete the time subjected concrete H 0 H time p; ct 15 during and reinforced time finding prestressed due dependent strains frames tt Ö and the rt 0 dependent their load the a11 in the planar geometric HOT concrete history service Hu distinct effects relaxation the concre the thi analysis displac 0 concre ሰተ ወ and live 0 m chapframes a D d fea-0 Њ the († 1) 1

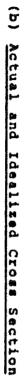
laxa stre due Ъ duct, ΩJ N O 5 ñ. stre n tion с† О tempe tn and o n o n e the s S 0 rature the loss ť friction prestressing the anchorage take history. creep ω between place during slip and shrinkage steel H the --postr and and prestressing the t n e after tensioned о Њ tensioning effects the concrete, transf steel structure 0 oper load and the 0 H ation of preú H @ | the - s † d the

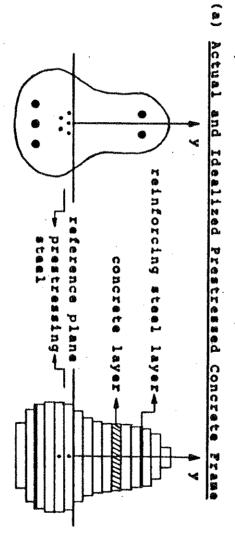
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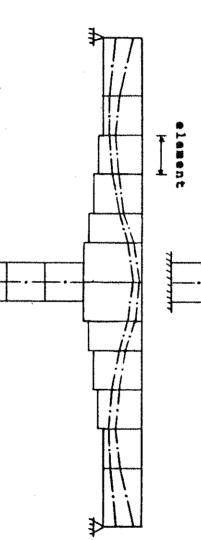


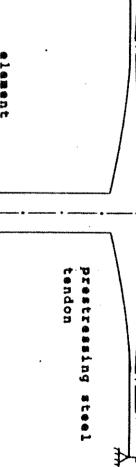












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S umption S are นรед for ъд рте n tres w ր Ա concre t e fram ō n

0 ¢, 1 H. Ó given ss-sectional rt с пе Th ø fram profile ге н. s n ٠ ۵ ۵ Ħ , initial tensioning area along discrete ach 0 Ξħ these number t t s pres length. 0 Hi tressing prestressing нон 0 and Stoel **D#** cons stee tendons 1 8 2 tendons rt រាឧទ

measured in the local ο The ſÞ Ø G Ъ Ht. ja. egmen Ψ Ō ρ Ħ the an d ង locations 0 ŀħ Þ rt ω two ወ ,Ω U 1 **ب** 14 ٢ħ restressing ø rame ¢, Ø end N μ r† H shown frame elenent ው 0 H element ssing points the two end н. Б ር። የተ steel Fig. 4 from and 661 coordinate ង ហ segment tendon the are defined 6.1.c S points បតាខ joints ք S consists rt Ö տ բ. each of which 0 Hi have and μ. Уď <u>D</u> and prestressing the ወ 0 Њ μ . .ب const are βu eccentricities respectively disc μ. the 64 5 () rt. н S Ð distanc н он traight () () steel กบตn ወ տ Տ

Ď. **...** 0 ment The culate ő ment 35 sioned Ø ű .ng Hh. teel 9 C 11 И the element hown ср в ср Ø i n H 0 H d. Perfect **j.**. iffness bonded element 'n segment dis an element Ļ, these assumed for 0 m tance stiffness ٦ ۲ bond Q of the structures. these parallel stiffness. structures 6.1.c from between is located at the depth of structures pre-tensioned structures 0) (3) prestressing the <u>с</u> μ. H the concrete بب ۵ reference the the Assume Thus calculated н. Сй и (1) x-axis the displacement gment the steel assumed plane prestressing 0 14 and ₩. (A segment р С the element rt 0 Ç۵ урз the follows М G D teel and post-tenthe mid-length # prestressing 5 continuous (e<sub>i</sub>+e<sub>j</sub>)/2 11 e layer havsteel and an eleр Д and within added seg cal-

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6.3 Analysis of Pre-tensioned Frames

6.3.1 Analysis ри († the Transfer 0 m Prestress

Ô. m prestressing erred to oncrete After 3 յ... տ The the the formed steel stre concrete initial ŝ and which r n prestressing cured. the following events occur. the р. 10 prestressing anchored Before Force 0 the the abutments steel is applied prestress յ⊷ ն relaxed -11 0 (0 the transthe

<u>ເ</u> The together concrete and the as the concrete prestressing hardens. steel are bonded

gether concrete н 0 after shrinkage analyze the (3) and 0 H stress in Shrinkage 9 C J the concrete structure for prestressing of concrete the take prestressing place these steel takes place 9) († events assume |---(8 the time steel is completely gradually. 0 14 relaxed the transfer that all bonded and n 0 1 the 90,1

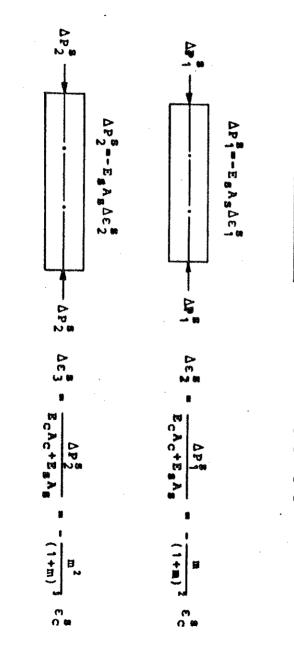
ple ິ ດີທ 9 CT 11 р Ф taken ties sioned remaining р. 0 the equivalent shown is given. The place concrete total analysis just in Fig. 6.2.a in which a concentrically pre-tenfrom free before the transfer load г Ф т prism the procedure shrinkage м Ч ъ С initial with 0 0 acting the linearly 0 15 69 1-1prestressing force 50 *illustrated* concrete up t n e after the relaxation in the prestressing elastic composite force 2 7 rt Ö material Çe transfer prism P0. simple d L e proper-Le t w exami ឯឧន steel then n se r† 0 n

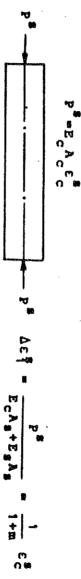
P<sup>s</sup> = EcAces

6.1)

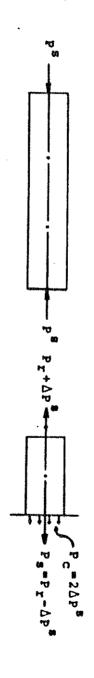
₹ig. ф • 2 Shrinkage Analysis of Concrete Prism Bafore the 0 Concentrically Transfer 0 Prestress Pre-tensioned

# <u>(</u>) Iterative Method of Solution









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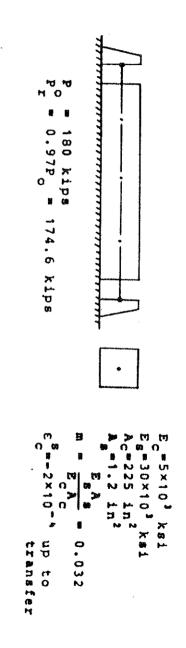
Concentrically With Given Dat

Data

Pre-tensioned

Concrete

Prism



the it B te e rt steel corresponding ∆es concrete embedded 0 the and i n amount steel the decrease prism 0 H prism change in the լ... տ due 1. D rt Ö force the the strain shrinkage Щ 0 Ц the 0 F prestressing t ne ကိုကို compos-Then

Δps Ħ t -ESASΔES (6.2)

Аq ው juđ The decreased . N. D the steel force amount between by the i n t ne Δps amount  $\Delta P^S$ , and the prestressing steel embedded 0) (A shown in the prism and the free body diagram abutments force in the ц Ц is increased the prestressin Fig. prism ր. 0

۵es tрe composite can be Then, the calculated prism. change Ъу 15 applying the strain the 0 forces the composite ю Ю and ∆ps prism, 0

$$\Delta \varepsilon^{S} = \frac{P^{S} + \Delta P^{S}}{E_{c}^{A}c^{+} E_{S}^{A}s^{-}} = \frac{E_{c}^{A}c^{c}\varepsilon^{S} - E_{S}^{A}s^{\Delta}\varepsilon^{S}}{E_{c}^{A}c^{+} E_{S}^{A}s^{-}}$$
(6.3)

Solving Е Д (6.3) for Δea

Δε<sup>s</sup> t ന റശ 2 m (6.4)

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che σ • 0 7 0 7 0 4 and the 6 statics 2) Ю O. () () can shown р С shown ц Ц P i T ð • b e 6 . N D Ø q u a 1 g 2 A P S which

₹e 0 14 σ മ material N nonlinear may Eq. 0 The c (6.3) ເກ ເປັ properties analysis the • forcefollowing However, displacement for the н т ր. Տ FOR iterative shrinkage generally complex relationship. procedure impossible structures is based ល ហ 05 цЦ сt С with the shown this ss CP rt nonlinear solution ц. Д n up such ល ហ Et g

- 3 culate Apply р s the . EcAces corresponding 9 the strain composite ∆es. pri S E and **O** al
- (2) Δps strain ц С Since (n 間 rt retched the । ल increment SAS∆ES prestressing steel ЪУ and  $-\Delta \varepsilon_1^s$ , apply ∆es s calculate the the connected corresponding corresponding rt Ö abutments force
- (3) ing NOW force ş.... 63 shortened the strain ∆₽2 2 prestressing Ħ increment -EsAs∆es , p.y. -Acs, Δe<sup>s</sup>3 and. steel (4) () apply calculate connected t ne the corresponding ő corre abutments -puode

ta The ments ults desired shown obtained н П strain Fig. ц Ч the Δε<sup>s</sup> 6.2.0 iterative can be calculated proce Q0 **N** Åq вy adding adding the the incre н Ф 1 t

۵es l ≥ ad ÷ Δe N 0 ÷ s aγ s + • 6 • თ

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Δp<sup>s</sup> ជ 0 without approximation which is obtained by applying  $P^S$ tion Thus that ŝ which given rt t-i on approximation erms 768 ∆p# 1 # due to ы. rt t ne represents The gives 0 1 r e subsequent n ΰ 6.977<sup>k</sup> the 81g. 3 error involved by using the first resent first shrinkage С С С s initial ő 6.2.a sď⊽ concluded that term only 0.12% of successive which the exact corrections 11 r D the exact can be prestress P<sub>0</sub> 6.767<sup>k</sup>. represents ы Ч solution, and corrections. (6.6) calculated by Eq. value the the This gives the represents initial prestress Ħ first represents 180<sup>k</sup>. 0 Hi C 0 loss the an acceptable order the With numerical data 0 m The order loss the rest 3.88\*. (6.2) and approximation the gives first 0 14 first approxima-0 19 loss prestress FORCe. the Note the valorder soluorder 0 m (6.4)

UA. 05 performed tressing the Then composite 4 1 1 6 н. Л steel a single step by applying the analysis 14 14 frame included. ርተ የ in which 8 L J transfer 0 1 1 stiffness 0 prestress following 0 F the сал preloads 0

- (2) () joint ing Joint Joint discussed in section 6.6 tion р) ст: 28 loads due to loads loads the time taken place. due due 0 F ст О 11 0 the the м Н the ր. 8 shrinkage The prestressing transfer discussed and the calculation calculation after of concrete 15 force the section 0 d Ы relaxa H н exis с Р of the н-0 ማ rt 0 ບາ • rt
- (Ξ) Dead rt ran ٥, 16 17 17 load since 0 Hi the most frame. 0 14 the. Dead frames load are н. СА eccentrically applied ω ct

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Ъ N e S tressed and wi 1 1 hog upward )) rt rt rans łħ, Ю Н

#### ີ. • N Analysis after the Trans 17 19 11 0 M Prestress

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р. Д 0 the reinforced aging history, μ. which UN. (A) (T) the analyzed stress ction Afte the 0 prestressing concre temperature H stiffness 6.7 for concrete the for the rt D transfer various by prestressing steel frames. due history, the time t 0 0 H procedure ö the prestress t he Calculation of dependent and prestressing steel element the developed the and creep, loads loads composite the the stee] due to previously shrinkage contribution are strain )---(1) discussed frame, live included and and for load 15

#### 6.4 Analysis 0 15 Post-tensioned Frames

#### ማ . 4 ----ði Analysis ри rt the Transfer 0 Prestress

Уđ stressing ing force duct, friction red tion. てわら end († 0 For away resulting formula the As with post-tensioned taxes steel the from concrete gradually during the tensioning the prestressing place (105)'n the force initial the tensioning Detween due gradual structures force ő force сре the prestressing ъ Ч end. decrease friction 1. 13 0) (A the applied shown The prestress 15 decreas can i n the fron 0 0 steel Fig. 6.3.a prestressing ø µ≁. 08 the calculated ín transfe operaand the the tensionpre-H

 $P_{1e}^{-}(\mu_{\theta+KL})$ 

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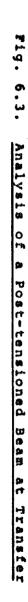
(6.7)

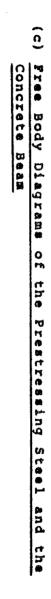
Ч ----H Prestressing force p) († point

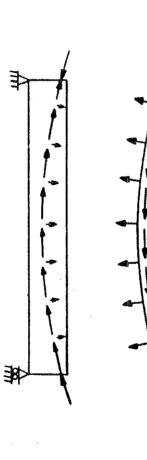
H erring rt 0 Fig. 6.3.5

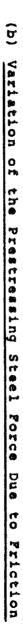
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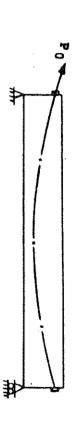








(a) Post-tensioned Beam with Initial Prestressing Force 0



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٣ 8 Change Fe ngth 0 Fi р. 2 the the slope pres tressing 0 F the prestressing steel segmen rt steel

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2 point With , 11 11 given Eq. along 6. initial tensioning the 2 ₹e tendon by can calculate starting force the from P0. prestressing the tensioning force e nd рі ct any

5 - 60 forces restressing 17 H. aight S ince 9# rt and t D e each steel have t wo prestressing end ç, segment constant points ₩. 10 0 Ha force, stee] taken the segment segment the () (4) the force )----60 average ц. Ц. assumed **p**# 0 specific h 0 с<del>т</del> 17 e G

and prestressing subtr strain tensioning the acted When Уq force the there Å end, steel the 15 amount ր. ն بب 1 each corresponding tendon, an <u>ب</u>. 0 0 Hi 0 Ħ anchorage slip by an assumed  $\Delta L/L$ , where the takes prestressing that decrease place uniform t+ թ. Ծ throughout t 5 e н п steel amount decrease the length force segments the ⊳ r 0 1 1 1 ው የተ EAΔL/L tendon, the the the ր. ն

040 H 1 steel Ø Ø H Ĥ 0 0 rt can Ø ting Fig. can tendon 6 0 s B 6.3. forces summarized and observed. n shows the between concrete ĝi K Free Then the follows. body the prestressing frame diagrams analysis рн rt transfer, 0 procedure stee the **ا**سو and pres μ. 5 the () which intressing ¢† trans 001-÷

Eq. (6.7) Å starting from the tens ioning end with

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ing given Ø teel initial tendon. tensioning force н 0 Н ወ ach σ к Ф ŵ († н տ ն Q 1

- 2 averaging Calculate two each segment prestressing steel end force () • segmen đ force ЪÀ
- (3) 0 Subtract the loss th 0 1 1 0 prestressing d u e steel segment to anchorage forces slip from each
- (4) procedure Calculate the described joint in section 6.5. loads due to pres rt H e s Ø Уq ų
- 5 and not which Analyze the included, the stiffness dead load. the plain or for the joint loads 0 reinforced concrete the prestressing du e t 0 steel prestres frame, н G ť n

#### 6.4. N Analysis after the Transfer 0 Prest ress F 0 T Bonded

and

Unbonded Frames

11 FO F the unbonded. After duct the .... (A frames grouted transfer for bonded frames 0 prestress the and prestressing left ungrouted steel

0 whi ſÞ ц. S ement tween r-h xcept 5 the analyzed For ր. տ the the 0 a rt concrete continuous, so that the composite structure, bonded unbonded structures stiffness anchorage points, concrete and the н 0 П frames the an d various time 0 ħ the the prestressing prestressing steel displacement prestressing and the displacements dependent loads there steel are is an interaction besteel field after ц Ч due μ. Ω and independent included p to fricstrains frame transfer. Ļ. H ₽ |---|

unbond tion. e Q н 0 structures illustrate the μ simple basic beam procedure with an unbonded for the analysis straight 0 m

and The eccentric ភ ០ material Ηh riction prestressing properties ۲. ۵ taken steel are into assumed shown account 5 ő 110 H Fig. 6 0 simplicity linearly ი • ф, ß μ. 'n elasti analyzed n

the obtained strain increase due lected. friction **O** (n rease teel concrete ő Le t strain μ. t he ហ уq ₽ Thi s between uniform live applying 0 0 beam ы. М strain the for the concrete  $\Delta P/E$ load w. the as shown throughout increase ; s A s the increase prestressing assuming following end moments The i n н. Э the corresponding Fig: 6.4.a 10 10 the рі ct tendon that the steel prestressing steel 6 1 1 0 steel the steel and and steel increase р. 07 the the level which and equal duct effec strain forces 15 **1** ы. Ю ct force 0 р. 5 the the negthe đ н. 03

(2) ()Eccentric imum Average bending moment at bending compression Ap at the moment the 0  $\frac{2}{3}M_0$  where midspan steel level. due °, W с† О ነ። መ ٤ the max-

p Equating the rt the steel strain level increase HOH the steel and the concrete

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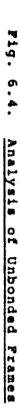
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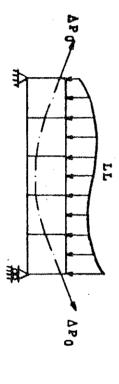
 $1+m(1+e^2/r^2)$ 

However, E cannot always 05 (1) (1) с Ф the equati o B H 0 H ₽Þ for

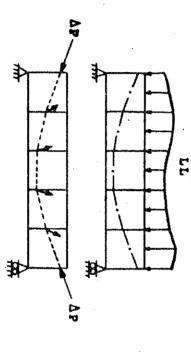
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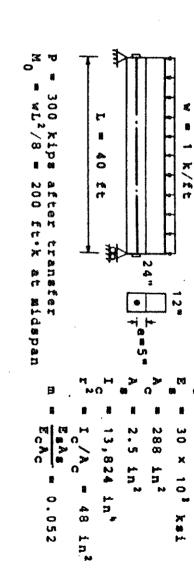
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whi lution, can th the Ht. complex 0 er, llowing 0 shrinkage in which the solution is represents structures iterative be used for general structures. analysis of pre-tensioned a successive with procedure, nonlinear material properties correction to given by a series similar to the frames с<del>т</del> 12 е procedure before previous each term of transн От The រ 0 1

3 Apply £ 9 9 the concrete beam. The ave н ω ú ወ Stra μ. B

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ŝ Ħ EcIc ø ω [ Ν Β Ο : r<sup>2</sup>EsAs 9 0

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The corresponding increase in the steel forc ¢ ր. Տ

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(2)Apply The resulting  $-\Delta P_1$  on the strain change concrete beam ր. Տ QJ rt the steel leve

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Δe<sub>2</sub> H  $\frac{\Delta P_1 e^2}{E_C I_C} =$  $= -\frac{\Delta P_{1}m}{E_{S}A_{S}}(1+\frac{e^{2}}{r^{2}})$ 

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The corresponding change in the steel force

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 $\Delta P_2$ EsAsAE2.

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We could go on by applying

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 $\frac{2}{3}M_{0} \cdot \frac{me}{r^{2}} [1-m(1+\frac{e^{2}}{r^{2}}) + m^{2}(1+\frac{e^{2}}{r^{2}})^{2}$ 

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'nd ----梋 8.667<sup>\*</sup> II 2.89 percen rt 0 m d

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D, 0 ŝ The take n m rt H н 'n Ø ssing approximation may be . error the ŵ -----Thus first +fi O ri force Dp e e N taking order IJ can conclude 'n 7.982<sup>k</sup> and that ∆P1 approximation t 0 0 ₩. 0 N 1 1 0 1 1 ٠ that 0.2 ტ ტ rigorous taking ---percent ju. Ct 0 M and rcent и Н-ΔP<sub>1</sub> 0 ⊨h taking quite 0 H ÷ ∆₽<sub>2</sub> t t t e accep the ທ ກ· total second table only ับ ห đ 0 0.02% ወ 0 7 i

duc 5 ъ assuming analyze Ĥ cting Ø rt S されの Т'nе ን የ ssing general unbonded frames the procedure 101 that friction between († 0 steel the Fig. 6.4.b changes described are uniform רי הי the t D e above can be throughout н 0 Н prestressing strain any and the time generalized the dependent steel tendon Force and Åq đ нон load t D e negthe

(1) Э The 0 H S H calculated Analyze ade et Ň Ø 661 Ψ. sponding 11 12 10 10 100 ave Ŀħ ents 0 force Ĥ, prestressing rage the each ъ the average concrete ທ ພ change Δe prestressing first given N in the increase ΣΔΓ/ΣΓ steel orde А Д frame ΔP н where steel strain for any approximation. Ħ steel excluding in the ы °. ₽ -3∆ε. the segment. live prestre forces summat 9 C 1) ትሀት D € load W Ŵ can ion indu ssing rt n rt The j... ++ ++ + H n rh н. Ю 9 0 Ω. ህ ness 001p.

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H 3 11 0 ភ្វារ ចុ the ¥ e the the such age this don. forces and force tendon distribution Analyze o 25 ъ tensioning operation. tendon equivalent tensioning calculate თ that oint distribution . ф ۵P The cannot calculate along the 0 n 'n μ. († can problem including Þ concrete the produces 0 14 and the р р 0 1 1 1 0 determined μ. the tendon determined can here total steel the distribution The frame 0 5 1 1 1 1 1 lies elongation effect equivalent determined total force Force Once fон Åq easily. ц. a D the the Δ₽o ΔPo elongation 0 M 5 n c 0 Fi iterative fact ₽₽ live friction rease ю М р) rt Уq tensioning the Assume 0 17 both anchordetermined applying that load the steel along ۵r that с) N method the tenн Н HO H t t t e ц.

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#### <u>ዓ</u> S Calculation 0 the Load Vector Due с† 0 Prestr ess

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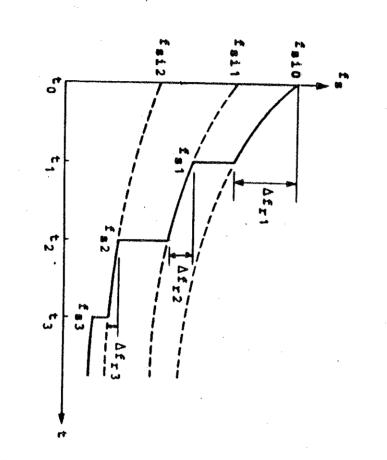
bed 17 ≥ t the times compression at ۲. H S ated harped 5 and sually straight and has a constant force. († For ransfe harped tendons are used to get forces the pre-tensioned points the н connection is removed at transfer. 0 M are applied to the concrete the two end points of the prestress tendon is connected frames takes 9 1 1 9 place prestressing the by с† 0 desired eccentricity. the tendon. ρι rt the the concentrated steel In this Thus concenprestressing harped points. But sometendon case

Å which generally has 9# series In ₩-104 post-tensioned assumed 0 a curved profile. straight rt 0 have frames the prestressing prestressing μ constant force. This steel profile is segments each steel tendon approximated 0 74

an Ξ Ø end ď opposite shows μ egment restressing ā, represents n onstant the points of the The <u>g</u> concrete AB with typical of the assumption that force the steel prestressing ω frame implies interaction prestressing steel segments. force and the concrete takes element ы each prestressing that ۱... ۱ between embedded. force н. Э the which interaction 5 the рі rt μ two end Application prestressing prestressing place only steel segment between Fig. points 0 M በ የተ ი . . steel steel the the Þ the and has

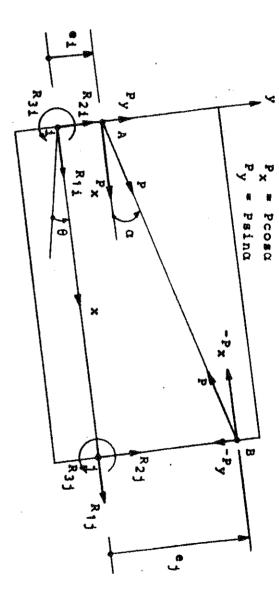
Ю × 1 Pcosa, The components \$ 8 Psina, 0 ψ where ۳-۲local R به: ۱۰۰۰ element 6 1 1 1 angle coordinates between t D B C T are 10-••

₹ig. ¢٨ . 61 Calculation 05 the Stress Relaxation





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et O, equivalent 57 0 <u>م</u> element × a x i s joint and the are load vectors prestressing  $\frac{R_i}{2}$  and steel segment R<sub>j</sub> at joints ∼j AB. ۳. Then and ч. the 0 Fr

 $\mathbf{\hat{R}_{j}} = \langle \mathbf{R}_{1j}, \mathbf{R}_{2j}, \mathbf{R}_{3j} \rangle^{\mathrm{T}} =$ <R<sub>li</sub>, R<sub>2i</sub>, R<sub>3i</sub>><sup>T</sup> Ħ <-Px, -Py, Pxej>T Px, Py, -Pxei>T (6.12)(6.11)

the 0 by multiplying the transformation matrix  $\underline{A}^{\mathrm{T}}$ (5.60). These rt transfer total joint load vectors are transformed into the By assembling these load vectors for can be obtained. load vector for the structure global defined by Eq. each element du e 11 0 coordinate prestre Ø ()e ω

ht Ø quivalent joint rames tressing An identical procedure can be used to calculate the edescribed in section 6.4.2. steel for the second order analysis of unbonded loads due to correction forces р. П t n e pre-

#### ሐ Stress Relaxation i D Prestressing Steel

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was æ Ŵ developed xperimental data for a wide variety of prestressing tress discussed The nature of the stress relaxation in prestressing steel based the following equation for the calculation of the in section 2.4. relaxation in prestressing stee Magura, Sozen and on numerous Siess steels. (106) -

- HA | HA - KA | KA - H<sup>4</sup>-I  $\frac{\log t}{10} \left( \frac{f_{si}}{f_y} - 0.55 \right) ;$ fy si ŧ٧ 0.55 (6.13)

stress 1 n immediately which and н. 0 rt after is the н. Ю time in hours stressing, stress рі († time t; f<sub>si</sub> <del>ا</del>ر م after stressing. 15 0.1 percent N H the offset initial stre yield w

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pre 2 suggested the 0 5 Ъ ٥, Ωi H н н et H lace ά Ø C D, ø ΰ Н õ n n 1 æ ŵ lied. calculation R rt ŋ ins tensioned H D n tr utilized due f† ,à о Ц П е Ś 0 (n constant take the following procedure. (б. varies с† 0 ЧŢр п† 0 --... other reality various thes structures, elas a similar procedure. of the relaxation, ۱۰۰ ۱۰۰ due to various and ŵ ct causes. ը. Թ j..... variations 0 the initial veloped shortening and One changes 0 n after i D time example the ыло, 0 Fn prestre Hernandez Ghali, transfer cond concre Ø dependent in 1 rt H ດ່ is the loss the ທ ທ ы г† ເກ ເກ rt . سو Sisodiya . On ወ թ. տ into prestress and the ው rt that the load rt Gamble account amoun rans only ທ t n e and 0 Fr Ph n rt tax D F e HB Η រ ក ក Ø (107) Tadro 0 train ч. 5 +n т О қ ወ 1 . មូខ ខ្ល

t.2. (De Вy O, tious β**υ** . مو Tdde rt ()) ы rt. ct tial μ. ۳Ċ alculate rt ous ress laxation н -tim continuing , це с ∆ F initial Referring prestre initial ø drops H Lui ц ц († Then, ۱--เก the ∆fr1 time can ť calculated this on the prestress stress prestress o O to Fig. 6.6, let н f<sub>s1</sub> due °, from the 0 1-1calculated process the applied basis of the initial relaxation  $\Delta f_{r2}$  occurring At rh. similarly 14 60 14to other time initial ທ |-| N ЪУ 94 r† which would ст 1-2 рÀ total S 10 to would be 년 1 1 1 causes. 1 2 prestress after (6.13) addition stress ው ሆ calculating the relax prest Calculate fsio, such relaxation initial relaxed r† 0 during t<sub>1</sub> and ő 100 that the the 1 10 10 Ø to fs 1 1 1 S 1 1 **S#** prestr 94 ١0 þre t ne rt. fictip) rt 13 10 10 ۲ħ ffoti-5 າ ກໍ inø N (A

 $f_{rn} = \sum_{i=1}^{n} \Delta f_{ri}$ 

(6.14)

ω ω

6.7 Calculation o f Pres tressing Stee l Strains and S rt R C w ល ខ ខ ខ

and Internal m lement Forces Due 17 0 Prestress

<u>ب</u>سو م ponents from HD joint i global. points. У Д (n ŧA rt egments resses, the first the HD figure, coordinates 0 Hi 0 which have global coordinate axis, r<sub>1</sub>, ណ កេ Fig. calculating the global coordinates rder 4 7 8 the each 6.7 shows current length of each of rt Ö current <mark>о</mark>Ө stage calculate is the the original global coordinates  $(X_0, Y_0)$ . (X,Y) total displacement 0 14 a procedure 0 Ha original angle the ក ភ្លា ខ the iteration prestressing end ¢ point r<sub>2</sub> calculate and 0 Fi process is the vector corresponding the ч С 0 prestressing steel steel a r e the element 0 13 the strains the 1 ¥ 0 calculated the current end axis 0011joint ð and

Ð (A < c† H B De luated in and For pre-tensioned 0) () the stress follows н О.Ч and each post-tensioned prestressing bonded steel frames segment the 0 7 Q

(1) Calculate the strain increment Å

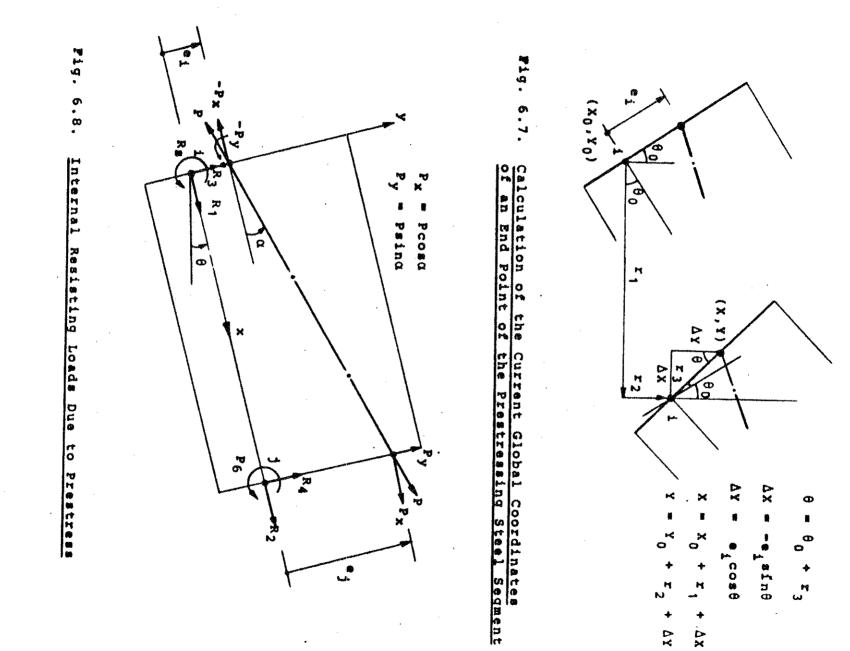
D e e H (L<sub>c</sub> ł Lp)/Lo (6.15)

frame the original eration, where original locations • element Ľ length. ٦ ک is the ыцр segment ь 0 previous is calculated 0 length the length two нон Гон end and L<sub>o</sub> 9 9 the points the current basis с Т 1 1 the the ы. ft t o Ha

(2) Add c† otal Δe n с† 0 train the ო • previous total ст О obtain the current

(3) Calculate the stress ő m h rom the

corresponding



(4) the stress Subtract nonlinear procedure obtained the نه ۲۱ ress-strain stress described ц ц step relaxation f<sub>rn</sub> calculated in section curve (ω) t 0 shown calculate თ • თ ц. П from Fig. t b e the 2.10. CUT-۶q

rent

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(4) ы calculated by crement represents 8 F 8 FOR followed ۵e post-tensioned unbonded for the a similar the entire prestressing for each prestressing length of expression as the the tendon. frames, steel steel tendon is Then average Eq. t ne segment. (6.15) in which steps strain first (2) to 101

0' 0 expressed Internal 0 8 resisting load vector follows TOT each element. 2 70 70 14 due r† 0 Refer prestress đ Fig. can 6.8

יים ייים . <-P<sub>x</sub>, P<sub>x</sub>, <sup>-P</sup>y, P<sub>y</sub>, P<sub>x</sub>ei, -P<sub>x</sub>ej<sup>,T</sup> (6.16)

0 ц. Д ometric used. which nonlinear relevant analysis, terms are current defined values in section of 8 and Ω For should ge -

270 ₩ a 1 1 concrete internal н 0 ң the α 4 α the ₩. 14 elements resisting load vector and structure transformed t ne rt 0 reinforcing form to global the steel, internal due to internal forces coordinates and resisting then and assembled load added vector for с† 0 F 0 F the the

-\* 36

6.8 Summary

from ing 0 analysis ħ prestressed chapters the The procedure 0 Ha features reinforced concrete except concrete distinct fон for tt he frames Some 1. 1. 1. nonlinear additional prestressed concrete р. С frames similar time developed steps t 0 dependent that which ц Ц for frames. analysis preceedresult the

рн c† Bonded loading and and post-tensioned The and after ч. Б analysis unbonded post-tensioned prestressed concrete the transfer is performed structures 0 prestress. нон distinguishing structures three structures distinct ~ namely pre-tensioned 978 stages distinbefore, 0 Ħ

guished м 0 н the analysis after 8 C 1 transfer 0 prestress.

ent **m** ()# ñ due incompatibility. prestressing ing assuming tensioned tive tr @ 8 \$ ontinuous. effects rt 0 Ç# HOH method method prestress н 0 4 that each bonded 17.0 }----80 is developed for For steal the displacement field within type prestressing discussed unbonded structures is developed. the evaluation A procedure 0 is added structure 0 1 post-tensioned the directly steel account for for • of the approximate For pre-tensioned and the including н 0 Ч to the stiffness determination tne structures each an element element stiffness the displacement stage time and and postan stiffness 0 0 dependloading due μ. M iterloadt L L e t 0

# 7. COMPUTER PROGRAMS

## 7.1 General Remarks

H¥0 CDC dependent puter programs had been written stage programs, 6400 0 m During this computer nonlinear the investigation NTRUSS course ρι ct analysis and NFRAME the 0 University t h e 11 0 procedures. present study 1 Were FORTRAN language of California, Berkeley. and written investigation verify 1 n the vari earlier ous н 0 Н 4 comthe time

ent ship lyzed temperature porated. t i Be effec يس. 10 dependent analysis HE by this program. assumed. the († 14 **Elastic-perfectly** variations d u e program NTRUSS ő Geometric creep, 8 K 8 0 Ha shrinkage included. planar a procedure for nonlinearity and the plastic concrete stress-strain and Example aging the trusses 0 m 4.5.2 nonlinear time dependconcrete relationμ. 8 ¥2S incor anaand

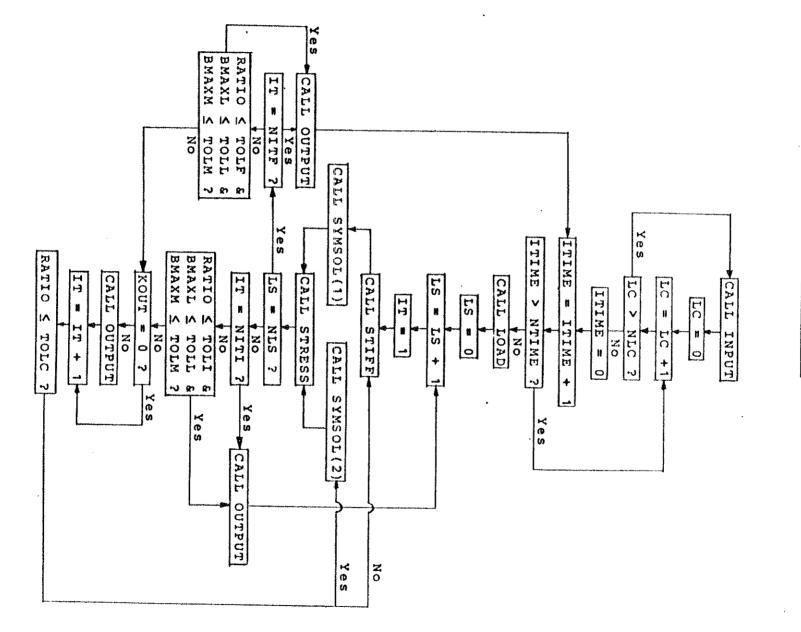
analyzed nonlinear lastic The material properties Åq program analysis procedure this program. NFRAME ¥ 0 5 were written for planar assumed. to verify frames. Example the geometric Linearly 8.2.1 wa s 0 1

prestressed cal tions procedures En FOR the these concrete programs are programs are incorporated RCFRAME frames, and given in respectively. for PCFRAME planar the the Appendix. reinforced The present input analytiand instruc

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7.2 Flow Chart 0 E the Programs RCFRAME and PCFRAME

ր. թ given 3 brief 1. D the flow following chart 0 Hi page the programs RCFRAME and PCFRAME



FLOW CHART

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BMAXM BMAXL NTIME . RATIO ITIME HOLC TOLM NITF KOUT TOLI NITI TOLL TOLF NLS とてつ н 0 H T rs S The INPUT TT e Main \*\* ... ... ... ... ... ... \*\* ... .. .. \*\* ... ++ ... ... ... 58 load Load Load ø Maximum Maximum Maximum Tolerance n Displacement load Maximum number Maximum number н Total Time Total geome Iteration output Maximum Tolerance Tolerance Total Var ompared with H, teration μ rt functions į. 1 on steps step ហ step Û, a b 1 e try, number number number rt Ø O ы 0 allowed unbalanced unbalanced moment ۲. ۳ unbalanced Ð allowed ហ н 0 г 1 0 1 counter counter H 0 H counter counter boundary н. 5 KOUT 0 Fh of load О Њ 0 Hh ratio the the changing intermediate load steps the following 0 m 0 the load بہ: ا unbalanced time code flow iterations final iterations . defined not subroutines conditions, Force o n steps (Output ct ases сhа stiffness Nero.) С, Ю load ហ h, н. Н н 0 4 HOR rt moment convergence step allowed allowed р Н Ф section 0 1--n t ne material listed ø given ն Թ current fined HOH For 4 are for ٠ properties ф. tolerance 1 1 0 1 inte ល ល ω đ C† Ø each нh Ŀ. final Η ollows. rmediate H Ծ Թ Ø ollows 1-1-1-ທ Ŵ rt С Ф

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Load concrete quivalent vec († and Ö H loads њ 0 Н temperature due the 0 curr creep, e 5 1 changes time shrinkage d at s μ. w computed including р ц ц aging е. Ц o r. n I

ω. S Ч

g Tange eome t 11 11 H V ທ and с† 14 15 Ρħ material ងខន S mat Ħ properties μ. × μ. n forme p,  $\boldsymbol{\Omega}_{t}$ ស ស ស ស Q, 05 the O. ជ HHD н т

4 SYMSOL

р, newly banded Displacement lready formed equation triangularized and increments stiffness solver ٠ matrix a H e SYMSOL(1) stored solved while stiffness Ъд triangularizes SYMSOL(2) this symmet matrix utiliz н Ч П the տ Տ

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δ 18 OUTPUT

The (a) step, following and н 0 н each informations itera tion are н њ printed KOUT ۵. ۱۳۰ 0 1 1 n o t HON N zero each load

- Joint displacement and rotations
- ઉ **p**art reaction forces and moments.
- <u>(</u> Unbalanced

- loads and moments.
- (d) Element forces and moments

(Moments

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Strains,

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8. NUMERICAL STUDIES

8.1 General Remarks

has 0 0 10 described can been ≯ number 0 U analyzed in chapter stated 0 reinforced and prestressed Уq ង ខ្ល 7. the follows The purpose computer programs 0 Ha these RCFRAME concrete numerical and frame PCFRAME stud-

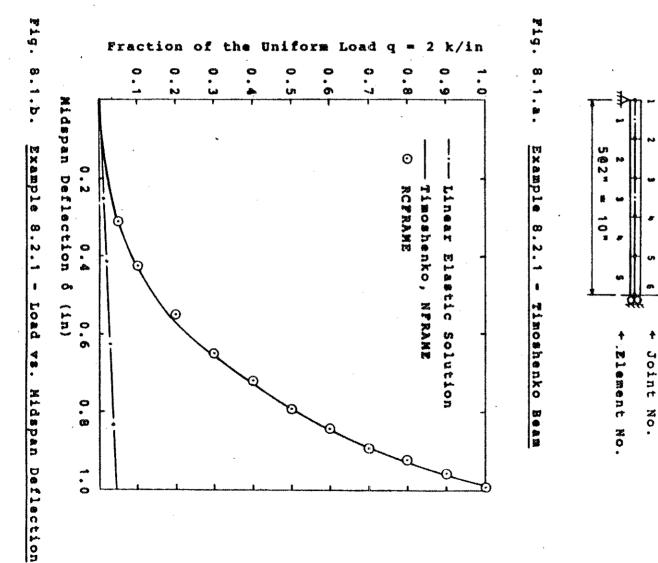
developed 0 H 3 reinforced in this study for the nonlinear time dependent н] О verify and the prestressed validity 0 H concrete the theoretical frames procedure analy-

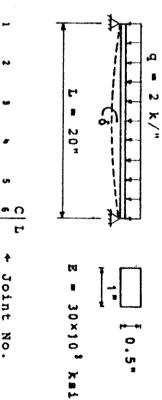
the concrete linear computer (2)t i 190 frames H 0 dependent programs demonstrate behavior RCFRAME and the accuracy 0 H PCFRAME reinforced and ц С 110 and predict capability prestressed the non-0

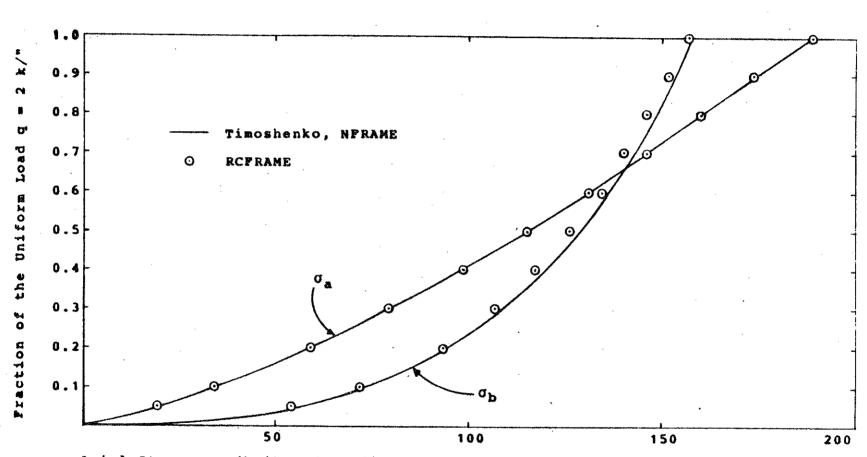
9 analytical programs mentally reinforced geometric concrete In section RCFRAME by previous and material nonlinearities results and beams prestressed 8.2, and PCFRAME, and the are are investigators theoretical presented. compared. concrete studies Ξp are frames studied sections and experimental analyzed on the effects the က • မ load Уd and and experithe reversal 8. \$ the computer 0

# 8.2 Theoretical Studies

က • and loaded nalysis N HH Timoshenko procedure order. uniformly, ст 0 1 1 2 2 3 1 1 2 3 1 1 Beam ρ simply 0 0 the ł shown Test accuracy supported 0 1 5 Geometric Fig. 0 beam, geometric ..... Nonlinear p, restrained н. Ю nonlinear analyzed. Analysis axially α 1 The







Axial Stress  $\sigma_{a}$  (ksi) and Bending Stress  $\sigma_{b}$  (ksi) at Midspan

Pig. 8.1.c. Example 8.2.1 - Load vs. Midspan Stress Curve

рі S i n the material the the д resence applied load deformed ր. տ assumed 0 Hi configuration, the axial 0 hс<del>т</del> О force 0 D increased linearly յս. Իդ s. structure elastic consider the becomes Howev equilibrium Ф Н • stiffer due ő

out t drical ő. this 044 Timoshenko surface. problem from <u>a</u> long treating (109) has rectangular the presented structure plate аn bending ы С analytic an elemental into al S ω olu cylinrt. strip

Уq layering tion nalytical Fig. comparison between midspan 13 1-RCFRAME beam د. د ements, .dspan, Yeb load ЪÅ ¥as 8.1.b, Since (100) 976 976 wa s RCFRAME steps of the divided one half solution The results the structure and shown in analyzed by and ն Ծ Cross Can those Aldstedt into to q of the . 19 Timoshenko's solution р С Fig. very for 10 equal layers section. N Нон attributed N the programs NFRAME and structure, divided 8.1.c. (47). the axial and bending the midspan deflection k/in. good. the This The loading to A small error H ft problem the Can Cross 11 0 H error involved and be seen that are the analysis section of the and RCFRAME into was the symmetric in the solu-00 11 1 10 S also are shown present СЛ equal the analyzed Åq ው ተነ about ť n with р; 1 e F 5

## 2.2 Reinf OFC e d Concrete Timoshenko Beam 1 Test 9

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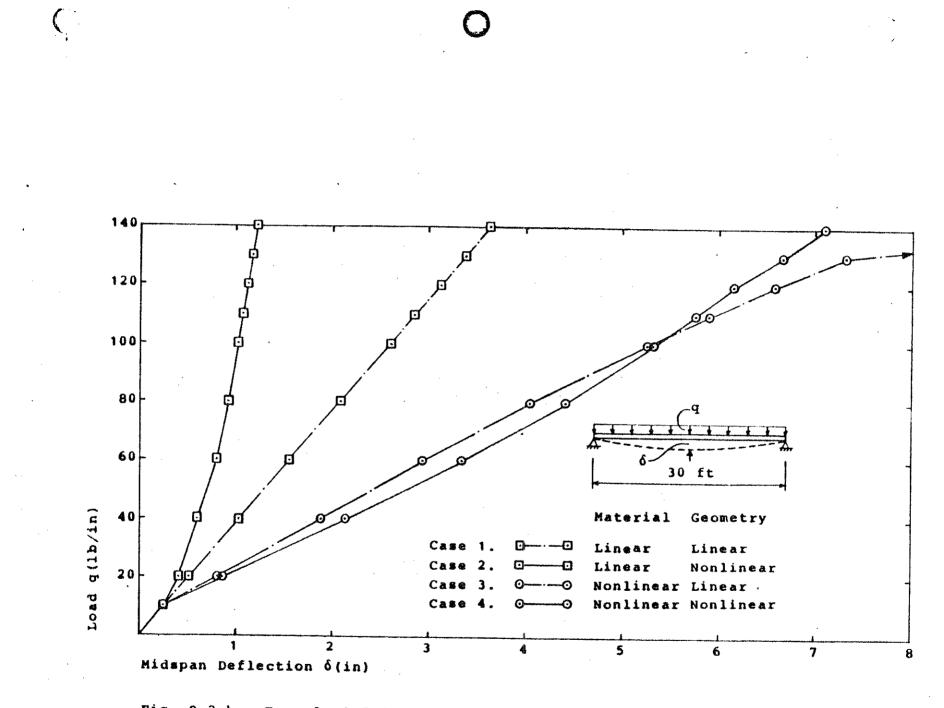
ρ († n ο the layer. rbi h 2023 4750 cross section the trarily n rt 1-1 section is Þ ructure structure nig. In order increased. 8.2.a, are 0 11 divided into divided summarized. increase the the compressive geometry into 10 10 Due ultimate and material elements concrete strength of the ő the load capacity layers is analyzed. symmetry propertie and concrete is only μ ω steel 0 Hi half The 0

manne ture nonlinearity note gradually initially Beyond the မ ရ t 7 e load increased both modulus ю Н-O, ц Ц Ц ß 1 o a tion : a s e ipan the considered. Ô. preceeding response. from H. stiffness level which geometric 2 CUIVe 10 11 steps. The structure load 0 The We notice a distinct stiffening of the 4 due as the load is increased. Fig. 8.2.b that further, we notice elasticity of concrete until it fails. due cracking load different рн 14 <u>بر</u> gradual Fig. to the effects d u e and increased due nt O Only geometric section. the cracking Beyond the cracking load reduces the 8.2.b shows load-deflection curves at nonlinear đ material nonlinearities is analyzed softening cases. the the structure can be I n yielding the single most geometry 0000 0 rt 0 of geometric structure stiffness that Case nonlinearity is considered and с б the gradual decrease concrete 3 only material nonlinearity t ne с† 0 ----0 M stiffening represents effects as However, μ. structure concrete Ņ р († 140 the structure important nonlinearity. are relatively lb/in ր 8 0 seen and linearly considered. ŀη stiffens load-deflecdiscussed the н. Э the load is softening with the In case Source ρ 0 Ha strucsudden Low effects softens t ne nidelas-0 X. Ø 1.2 άŢ 0 \*

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₽ig. 8.2.4 ٠ 140 Example Steel Concrete Cross Finite Element Mesh Structure 10 m , 19 00 Section Properties 5@2 ' 8.2.2 N 8000 psi 3.834×10<sup>6</sup> 60×10<sup>3</sup> 29×10<sup>6</sup> Properties M رب \* and -N 03 1 Concrete c.g.c. 10 3 0 Geometry and Material Properties 8 Loading 8 8 8 8 4 4 ተኪ በት T & C Laye -Layout Layer • 501. te e 1 II 2 -**М** на 8 N rt -775 S ¢ دما • ₽ 0 t x 8 2000 2000 ٣ 46×10 5 ŧ ŧ Joint Element ps: NO. No.

A



## Fig. 8.2.b. Example 8.2.2 - Comparison of Midspan Deflection

3 and	Axial Force P and Be	1. Example 8.2.2 - Con
	Bending Mon	.2.2 - Comparison of
	ng Moment H at Midspan	f Deflection 6,

Table

8.1.

à	δ(in)	n )	P(X	P(kip)	M(in·kip)	kip)
(1b/in)		Case 4	() 2 2 2 2 3	Case 4	Case 3	
10	0.26	0.26	3.8	4.4	162.	161.
20	0.82	0.86	-7.2	-3.7	324.	327.
40	1.88	2.14	ເ ເພ ເພ	-16.4	648.	683.
60	2.94	3.34	-54.0	-10.0	972.	1005.
80	4.05	4.41	-70.8	6.5	1296.	1267.
100	5.26	5.31	-86.3	27.7	1620.	1472.
110	5.90	5.75	-92.7	35.7	1782.	1576.
120	6.58	6.15	-97.9	44.8	1944.	1668.
130	7.32	6.66	-102.3	45.1	2106.	1805.
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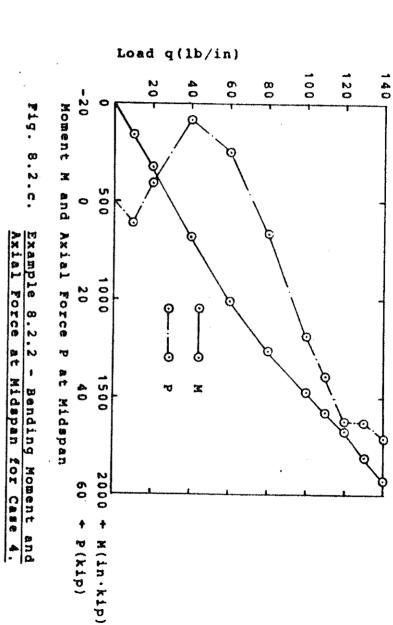


Fig. the concrete (A 8.3.a tructure Þ hypothetical reinforced concrete simple beam shown structures (8 |--19 analyzed to study the divided into subjected to load six elements. behavior of reversal. The reinforced One cross half 0 0 0 1 í n 0 Ha

## N س Load Reversal Analysis of ß Reinforced Concrete

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by Å the ы moment 0 0 0 load rium equations are solved in deformed state, the value of midspan, the effect of the axial force P is neglected, and deformed Q) H ው ct ø X the axial force X seen in Table 8.1. axial tabulated. M μ midspan are plotted in Fig. In  $qL^2/8$ ₽-00 X  $qL^2/8$  in this case. case at midspan. state. force increased, । P0. ω M is proportional to the applied load q as 'n the Thus in calculating the bending moment is increased. P is included in computing the bending 4 The bending moment M and the axial force equilibrium equations the portion The bending moment The bending moment M can be computed However, 0 8.2.0. the in case  $4_F$  the moment R We note that 0 H (0 can be and the effect solved resisted computed equilib-1 1 as the can Å **un**at at

The fin bending Ηn iterations per ē Ω addition results **р**. 0 H moment section 4.4 was taken 0.01. cases 3 and đ for cases load step was 4 Ж Al the deflection  $\delta$ , midspan corresponding to 4, displacement 3 and 4 are summarized in Table 8.1. for case the ratio axial The average ω and tolerance p force each load step <sub>ل</sub>م for case Ы number and പ ര the 4 0

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0 age the quired With 0 н 0 H Ťh n 4 n geome n μ C† numb displacement ង ខ ស ខ ព rsed the The t 0 load 4 ō 市よる国 0 1 4 load Ħ and con analyze 0 Hi μ. ທ ñ nonlinearities o increased entrated 1nc iterations per Ω rt 0 lgai ratio H for 4 0 ment Ħ kips, reversed load this ďn tolerance 0 Hi r† 0 sequence. Д then are load L applied kips, and 40 0 not 0 0 0 σ kips step is 11. incre թ. 0 included N 0 dire ւր Ա ~ Ч О Н taken 0.01. load and ased midspan ction of each then s t Ø а Ц н Н The ซ rt 0 load thi Ś ርተ ጋፓ ው **5**.00 сh е w рі Н 40 Ø ø The aver H 1-H 14 14 v n direct analys tep, SGTX н 0 H 0 ወ S 50.0 ր Դ rt μ. ro r ե. Տ 3 1 μ. 1 ĺQ.

p, Fig con N ω distribution Ω ele material et 17 (1) q ц в Ч  $(\sigma_1 - \varepsilon_1)$  and 0 ц N ĺΩ. orresponding Ň E rt H ¢ alon ñ ٠ ment resents м N 8 • 3 • d H () rt. and nguishing ö The በ በ Ś. represent NO. 005 the the n codes, results shows tress-strain curve, the Ô. tbe ማ H. cracked through length () rt • († 0 9 C 1 1. • 0 • deflection at Ø top 4 5 6 representing each ር የ the layer compress -0 Hi fiber stress+strain the midspan are zone ወ stress, load \* the inches respectively, at depth (a2step. bea μ. . ∀e various material strain values midspan. , H .е 2) are defined apart 0 ħ S ct H tabulated բ. տ • e s the H n CUIV respectively shown N fron Fig. CTOSS zone, () () However, 0 Hi the the ц Ц h α • t n of the 0 the ω • Φ section, the section middle midspan Table each states • • \_ \_ rt 0 0 0 ensi the ρ ひ o t t o 国 it. load rt. со • ۳ م 0 11 midspan 0 . مبو р Н-0) () in L 2.2.5. Hh N n ٠ н and fibe JUB the step S well ល ហ and rt 0 S ド市協議 H

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each 0) C ŝ በ 0 Ph ÿ, briefly which consists уd dividing 0 m 4 н Ц С load steps. 20 load steps into ហ groups

Ξ Steps 1 to 4 ( पि = ° × to  $P = 40^{k}$ )

с Ф The the steps edly bottom 11 0 beam Ø increased lope ų step fibers, and at midspan has 0 m The N • 4 shows the cracked the load-deflection curve at beam as shown and Between steps t he exhibits midspan deflection at moved up as shown in Í ₽ig. almost N and 3, cracking takes stiffness. 8.3.b. linearly The midspan neural elastic step 3<sup>k</sup> between 8.3.0. axis behavior ր. Տ place mard-0 H H

(2) Steps 4 to 8 (P ∎ 40<sup>K</sup> to P = 0<sup>K</sup>)

remain cracked during

the unload-

ing P the The а S 1.5 4. С С computed þ which fiber compared constant. cannot small t n e ω explained structure stiffness 0 0 modulus Accordingly, the stiffness is increased. 0<sup>K</sup>) due numerical error. t s at midspan shown in be closed as long figure that there zero load as shown in Fig. 8.3.e since amount of residual stress present may уq greater than the to the stiffness However, we note that this stiffness is increased Cracked of elasticity the by examining to the unloading path with the initial layer regions integration However, during this unloading н. Ю as the strain states secant modulus between Fig. 8.3.d. the between steps 3 and is the same as the some residual stress-strain curve total axial յ. տ zero In an unloading path strain forc initial modulus 4 0 U remain positive the cracks E P remain Ø ն Մ also note steps 3 considered 0 m ա ct This can modulus. step the almost midspan and ω top

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rt become ٨t ö œ the (J) Load same stif Crack 0 0 H D H reversal those њ 0 н patterns the path но г same for step 0 ⊨h the reason steps 12, bottom and <u>-</u>α ល ហ the rt O explained fiber 15 remain structure р ct midspan њ о Ĥ essential-G tt H-H-ហ rt Ø Ъ fness 4 G 4

4) steps 12 ф 0 -1 6 ٩ ٩ 1 -40<sup>k</sup> ő Ы 11 <mark>%</mark>

sinc wider higher becomes HO H ++ r† = top The displacements đ n o t strain explained E B the 10 rt ŝ 'n e X isting 0 S rt and 0 0 ω ø 97e ወ 9 1 1 9 1 1 fibers reason j\_ N beam Due shown that the region place 0 compressive corresponding هد. هد: softer note reduced. initial place compression († are У Д value 11 10 0 corresponding ⊉ ທ i n as shown for this the between ល ស the now in Fig. the are Fig. when the cracks compared 0 14 residual shown downward presence closed, upward :⊳ 0 increased compared stresses. 8.3.b. the lower н 5 01 10 steps с† О 8.3.b formed ţn ц. Б Fig. tangent consequence shown stress н ст = с<del>т</del> О đ load Fig. and loading. compressive 0 Hi cracking φ that for that the cracking Structure is reduced 8.3.4. and previously 11 the fibers compressive Ч 8.3.e. Also, reaches modulus ր. Մ cracking Fig. 10, applied load 0 14 Hence the crack The instead ď strain, stiffness 8.3.0 compared to the 11110 ц ц becomes load downward loading those њоқ cracking participate the residual 0 14 bottom propagates ជ ប tensile 301 108 and upward P 0 H t De the for cracking ő in steps lower after cracking Fig. betwe 40× t op downward ր. տ fibers tensile the strength strain assumed 9 1 fibe in re 8.3.e ¥e н 0 1 rt 0 cracking can value load S load ω firs rt Ħ 0 0 U đ μ: Π s Q D S I. th ť • rt

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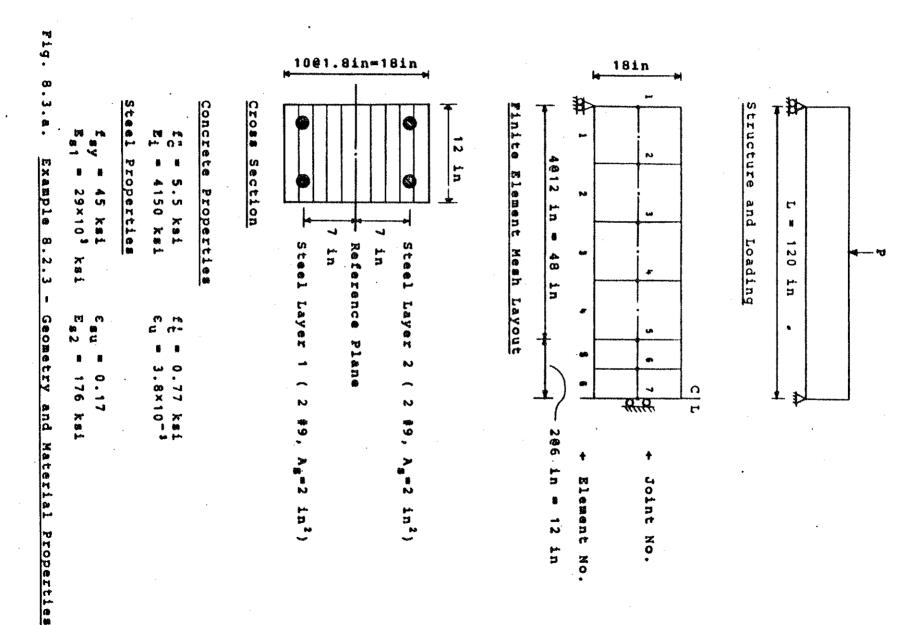
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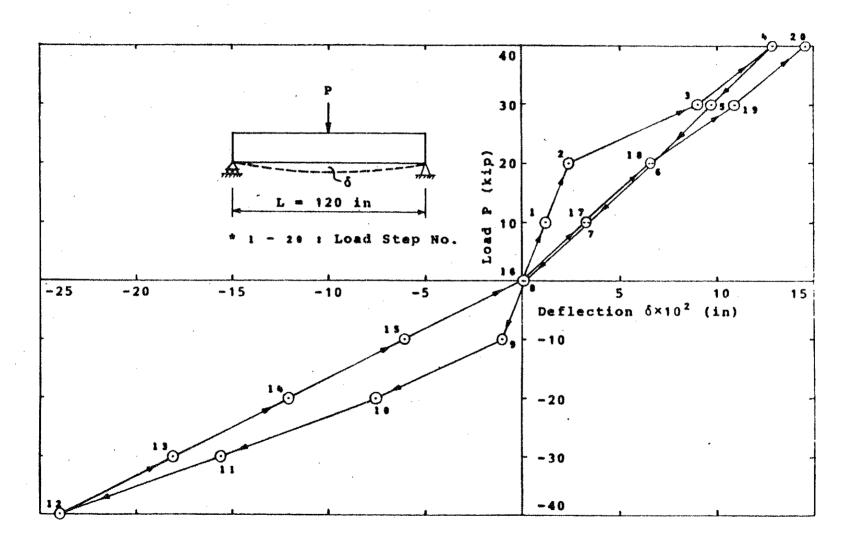
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## Fig. 8.3.b. Example 8.2.3 - Load-Deflection Curve at Midspan

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Table ¢o . N Example ω N w) ÷. Summary 0 Results at Midspan

Step NO 19 8 and 5 Load د. ه ÷. -10 ū -Ŵ ω U 1 w N -1 -10 F 10 **o** 10 5 10 io 0 50 10 o 10 10 10 10 5 (X) Δp O -20 1 Ŧ - 30 - 20 30 1 80 20 õ ů O 0 · mit -20 ω 0 40 ω 0 20 o ه (۲ o 0 O . -18.08 -23.98 ŧ 10 -1 . 1 15.64 ŧ ♣ **.** 0 X X 0 نبا • 0 б**л** (in) 7.64 2.93 8.98 0 نبا ہ ი • 9. 2.45 . 09 ი ს \* 5 0 07 N N 0 08 8 37 ა ი 1 22 N 5 Code Xat. -,19 10 . . . \* 0 æ de, œ œ 00 œ Bottom -2.83 - 4 . . . -3.89 I. 0 σ<sub>1</sub> (ksi) O 0 • O o -0.30 ω • 0 0 0 0 O O 0.65 0.32 . . ο ω ա Ծ <del>б</del>7 ч ţ. -12.27 ŧ ł b -8.23 -\*\* m ÷0. -4.11 12.15 10.87 ິ ທີ -8.04 × . õ 7.61 ىنە • 0.73 0.13 3.71 \$ 7.29 9.6 andi W • H 4010 ω 7 -75 0 ίN ω <u>а</u> С N **U** -1 0 œ 012 Mat 0 10 Code --0 O . ÷ ð œ٨ ማ ማ ማ N N Ð N -÷ -0.82 Top . -0 . -0.87 -0.38 • -1.47 -0.64 -0.32 σ<sub>2</sub> (ksi) ----Ο 0 O 0 o O O • • • ٠ ٠ เง 00 74 فيا 8 44 ш б hđ 00 . 7 D @ H ł 1 . ŧ ന 1 12.18 -0.20 -2.56 -3.74 -. 2×1 -: -0. 4 Ň ين • 0.02 6 -4.93 -3.83 1.36 4.05 8.11 ъ • 0.60 00 ٠ ٠ σ 5 5 **4**ω 9 25 -mite ω 89 ٥, 5 8 78 o ω

m ٥'n

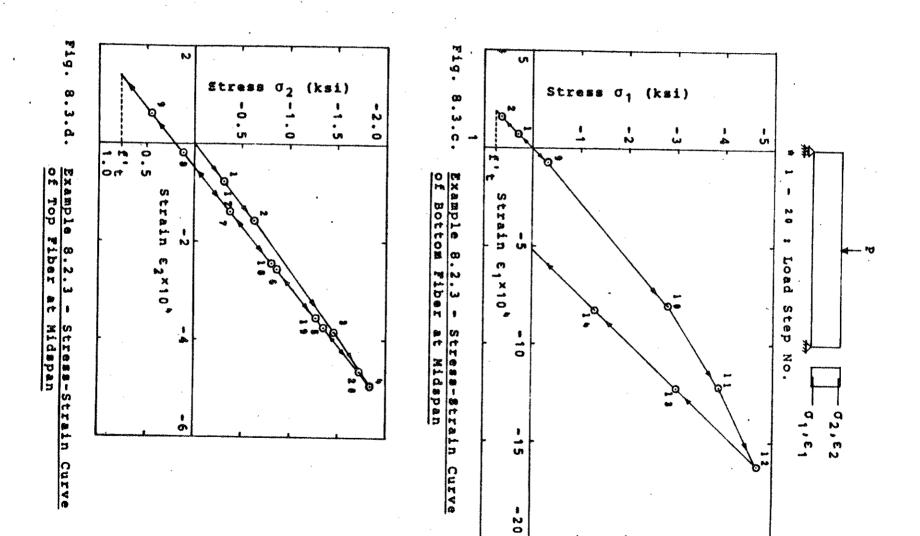
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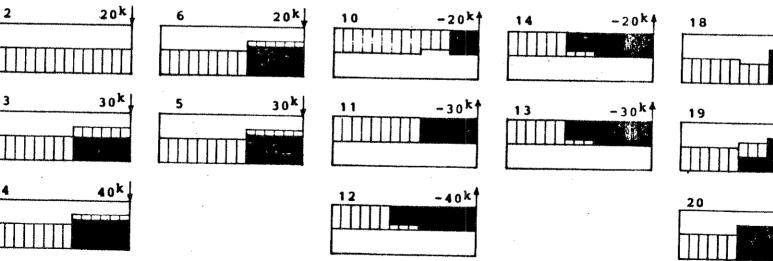
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Compressive Stress Zone Tensile Stress Zone 20 : Load Step No. Cracked Zone 0k 8 16 ok4 1.3 10<sup>k</sup> 10<sup>k</sup> 1 7 · -10k4 -10<sup>k</sup>4 9 15 17 12.14 20k 2 20k 6 10 -20k4 -20k4 14 18





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10<sup>k</sup>

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analysis divided beam forcement ч. С One divided into half details Web 19 0 reinforcements into concrete t ne ነ ት፡beam loaded shown 16 elements layer ц. Ц Fig. are ú and 4 , and at midspan, not 8.4.a. the included steel cross section One layers with half ц Ц µ. ts the H O F 0 14 analytreinthe 0 1 1 1 1 ы. Ч

study. flexural failure tests Bresler 0 modes ρ mode series and 0 Hi and Scordelis these beams. of reinforced designated by (110,111) have ⋗ concrete beam simple вз, beam, ր. տ beams conducted selected failing сt О study numerous for ы. Ц the this μ

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the 8 T 8 also crack open initial subjected to ц. Ц increased propagates the previously cracked bottom fibers as ≫ ശ downward the accordingly compared tensile stresses. <del>с</del> downward Q loading. wider load region is again applied, and đ Դ Տ that the the displacement load corresponding 5 1 1 1 1 soon cracks increased ດ ເຊິ they H @ | ч С r† 0

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301 note confirms the the shows Η bottom stress-strain 5 some esis ω negative the ct steps residual any fiber assumption tensile 16 ա. Տ value CUIVe г† О stresses cracked 20 (P = 0<sup>k</sup> to P 0 ħ stress that previously յեւ տ -4.11×10<sup>-4</sup> shown on d d d d d d d d d d d d d d d d d d d at step ٠ rt O ⊅ rt ц. dets numerical \_\_\_ თ Fig. # (see although 40<sup>k</sup>) cracked **ქ** 8.3. Table (h error Ω H ٠ fibers the ੁੱੱ 8.2). ⊼ີ ຕ £ ທ rt 9 0 Ø H (Ť This ր Q Can-ከ ከ (D р Н Э r: ;; Þ ω rt

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ŝ σ ., shells. ,cal late ۵ ñ tion model. elements 0 T 0 The similar element でよう for his (ω ]) to those used by Lin. division and also study analyzed this о њ reinforced the layering beam concrete with 0 the cross layered slabs and

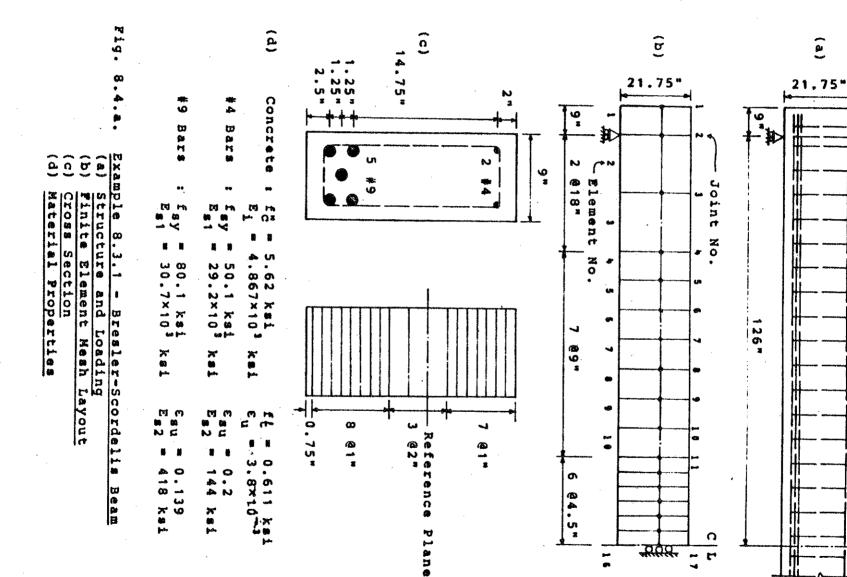
¥as łth. puted ĺIJ 4640, secant F O 田 4867 this 4640 ы Ч м а 0 8 and modulus ksi. terial study, ksi. (2.11).follows. н Ω= N properties the of concrete measured at 5.62 ksi, Since parabolic stress-strain curve is utilized The initial From results Eq. (2.10), with solve for are modulus also a 1 0 \*\* shown °0. ы Т е С 0 Hi the . 1 n Then q concrete can 2.309×10<sup>-3</sup>, Fig. stress solve --ksi, e<sup>m</sup> 8.4. 0fi -1. 104 and  $E_1$ ຸ ພ 0 0 년 2년 Xsi The 008-~

Ω average reach luded. In the ultimate load. the number With the displacement ratio tolerance of 0.01, the present 0 14 iterations was analysis, Only material nonlinearity Q load ማ Der L steps load were step. required ¥ 9 8 - 11 đ

one t, load parison. ent anal loading. CULA plotted. loaded ø (D Hh ytical cycle. Ø analysis Was цТ shown in Fig. H ects again Fig. In first ц Ц Experimental and analytical results, results 0 m The difference 8.4.b, с D both analyses, the and Lin's applied load t 0 experiment, about 30 in lower the ultimate load. 8.4.b corresponds load-deflection curves at midspan reversal. and removed. analysis, are shown together between the load level the midspan Both analyses And đ percent can experimental The load the second cycle then the տ Թ load-deflection was predic of the ultimate attributed both by presapplied beam was rt and fi O r the 0 1 1 0 0081 917 a H с† 0 ц 1 1 0

(n mates **O** 79.5 rt mental result н tima analyses an train Ö esult Lin's 0 0 rt D kips. concrete curve ЪУ attributed load analysis follow present 0f Although for concrete compared stress-strain curve ဖ ၀ that с† 0 analysis kips ļ. the which the for rt 0 compared fact load-deflection the ₩. 02 the elastic-perfectly сал assumed. experiment that result e D rt O seen closer with present the ъq experimental QJ fairly Lin's curves parabola as opposed analysis plastic analysis. to the expericlosely, for both approxivalue () († () the 0 0 0 This 0 łħ

and the ial law the 40 <del>امر</del> ا digits errors zero, section parabolic ultimate load linear \* FOr 5040 force depth numerical × H H 09 |--ĺn present (126-4.5/2) 00 |--table reinforcing steel. -0.018 k.in and Ö H 11 12 0 stress-strain law as assumed, presented. the 8.3 the the (40 integration computation. (P = 80k) are tabulated. result kips, 01095 bending ≍ 1 1 1 × and layer strain and stress distributions 126 from not and the bending section Total 4950 k·in, is 4950.21 k·in. 0 m moment 1 1) Also; statics In for concrete axial ы С respectively 94 11 the carrying 811088868 pø rt (5.54), the computer force, midspan, moment, which center enough Strain and are are check which output, the 0 evaluated computed by 6.80×10-+ distribution significant element should for the cross bilinear the should Small through ъ Ч с С kips **1**6 a x the Ծ Թ 98 17



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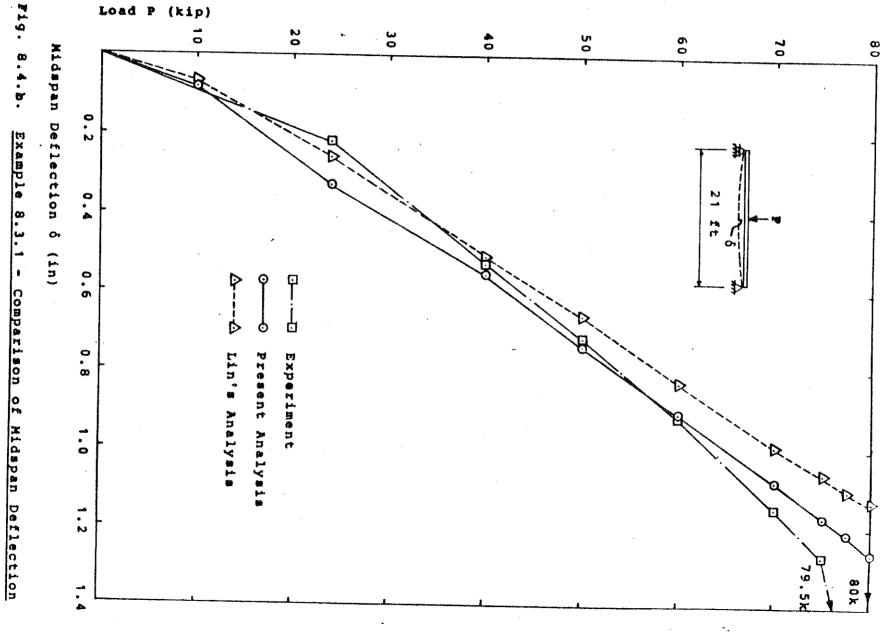
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Example 8.3.1 - Stress Distribution and Statics Check at the Center of Element 16 at Ultimate Load (P = 80k)

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Table 8.u.

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	Ste	el	Lay	ers	<u> </u>							Con	cre	te	Lay	ers					<b></b>			_ <b>r</b>
	4	به	N	· •••	19		 	5	t,	-		12	هب هب	10	6	60	7	Ø	in	4	ω	N		Layer No.
	2.037	1.0185	2.037	0.3907	6.75	•	•	9.	<b>9</b>	• •	9 •	9 •	9 •	18.	18.	18.	9 •	9	9.	9 +	9 •	9 •	• 6	Area A (in <sup>2</sup> )
	-10.25	- 9.	-7.75	7.	-12.375		-10.5	-9.5	+ 00.5	-7.5	- 6.5	+ 5 • 5	-4.5	- 3	1		2.5	ω • 5	4 • v	ហ • ហ	ອ • ເກ	7.5	8. • 5	у (in)
	2.466	2.154	1.843	-1.835	2.996	2.777	2.528	2.279	2.030	1.780	1.531	1.282	1.032	0.658	0.160	-0.339	-0.713	-0.962	-1.211	-1.461	-1.710	-1.959	-2.208	Strain E×10 <sup>3</sup>
Total +	75.70	66.13	56.57	-50.12	o .	0.	0.	•	•	0.	0	•	•	0	•	- 1 - 5 2 8	-2.933	-3.707	- 4. 349	-4.861	-5.241	-5.491	-5.609	Stress G (Xs1)
+0.018	154.201	67.353	115.233	-19.582	٥.	•	0.	•	•	0.	•	•		•	0.	-27.504	-26.397	-33.363	-39.141	-43.749	-47.169	-49.419	-50.481	σ×A (k)
4950.21	1580.56	606.18	893.06	137.07	•	0.	•	•	0.	0.	0.	•	•	•	0.	27.50	65.99	116,77	176.13	240.62	306.60	370.64	429.09	-0×A×y (k・in)

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# of a Continuous Beam

Thi Ω ١0 Ħ (A) lavi tud H P ΰ a D († () n μ. о n rt Ø н Ф Ħ Washa simple ρ. (n under inforc ր Ե c† нe followed and Ω. beams ល ដ ល ed n pendent hj concrete tained luck thei (112)H behavior load continuous earlier 0 с ц onduc tt Ö Ö H1 test 11 0 ನ ಸ್ ω Q, beams 4 series rt 1D (113) 0 M Ŵ н rt ហ ١O rt 0 ω 0 ц. Ц o ÷ħ Ű +h rt Ø study μ H н which 00 10 ը Ի, سر ပ်ရ nforced т. 1 Ф their ıding the S 0 Hi 4 Q, 007-10 1 tt ¥ O

sile W The 14. χ ដុ ц С Thei Ъ Compress section, cons applied þ Ð nally 4 igati ŵ н Ħ has rt 0 X uniform ы. Ю ĥ, educing and × Among . ⊲e N and ct G geometric **Q** Ц ----٤ ive lesi Ø compressive л S momen years ъ 0 K have Ö ×ω Ħ day the gned with ş., n load the reinf 1 t₩0 ч. ø added Ń were r† tensile after reinf continuous regi effec after N 0 properties orcements which rt O H S 0 H 0 1 n et. ACI rት ທ reinforcements. loading. 1-10 0 and study cement casting spans n includes 0 m **f**† specifications н Н Թ Ը compressive beams ц Ц are creep the the HO K (I) loaded uniformly the only 0 Hi shown Both effe positive the the ሰተ በ and conc positive S whi rt Ø dead n beams present ці П ŭ shrinkage s S S H . ⊢ © The reinforcements 0 11 was 0 m Fig. D two momen load Beam -• CFOSS moment ი • an thes that beam analyti with Q. ຜ • ບ • X rt  $\mathbf{X}$ 0 ø the rh. n н α = ١Ņ 0 H has reinfo rt μ ection egion, • н Ю 5 € Ħ • **.**... cal Ω ä. Beam 9 ខ្លួន 購 est. 0 0 i n Ъ Each , g o ø -1 0 Н SOH ւ**է** Ծ rt an ហ ĝ orig ω rt D a 5 O r† 13 хз. ements H ወ j. udy ω 0 H tena m ø S 3 μ, beam lb/ft. rt መ ቢ S ø ŧ Ω,

ponding **...** F vidin ĺΦ. midl S ince q eng rt 0 μ. 'n. rt rt the t ne 0 F support, U structure locations b b ŵ 9 ß lemen one and 0 H half rt maximum 'n loading . 0 M Loca the deflection, are tions beam poth U • ¥ a ų symmetric , ia and maximum analy  $\mathbf{z}$ • N M O 0 ρ. about 1500 FRE-Å

n

**D** 

CT.

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d u e n Ω, tion itive 1001 redetermined ð ۱---(A layers. moment the generally redistribution of internal forces. and maximum negative moment, although their exact locations vary slightly divided into -1 5 concrete respectively layers The and Cross sec-N are 0 w

Experimental creep and shrinkage data are not reference 112. O lng the assumed. sent 0 1 detail ties, \*\*\* rete Þ Fig. the experimental values of the strength, of concrete. secant the with Material recommended by ACI Committee 209 (56) and described in in chapter 8.5.b. average values The increase of the strength and modulus of time are shown modulus, E = 2835 ksi at o = 1575 properties However, Formulas N V The weight are used. 0 Hh in the earlier test on simple beams used in the analysis for in Fig. type of the concrete time dependent concrete ≈ The numerical values 8,5.b. beams at 14 -Hn () = K psi which repregiven in the days after ណ្ដា ព្រ N 146 3230 summarized 0 0 1 0 T 0 proper-1000 psi and based ы. М 

data with present 1 1 1 0 Åq ditions. unction nalysis. Washa span similar concrete mixes and under similar measured in the continuous developed in chapter 3, i. e. length of the beams were identical to those of the and Fluck (113), the cross sectional properties and Thus it was decided that the creep and shrinkage Utilizing beams. the simple beam expression for Both experiments test b e the specific used were н С П laboratory conconducted t ne creep present

Ω (T, t-T) 8  $\frac{3}{12}a_{1}(\tau)[1]$ ı. e-10<sup>-1</sup>(t-t)] Hh.

<u>p</u>

(8.1)

plac and and Spec ¢0 and tion was n wer а Н σ were ١Ņ toleranc õ D H ŵ ludi in L rt • ø ø . بىر 90 910 s t r nkage 14 15 15 S performed ң Xω æ use b used rt н ā , 120, Ħ ¥e prior loading. ime Q ains days the the н Ĥ Ø ρ ø n creep 0 H during after curve ste spe requi h ⊬ H ŝ were exper 0.01 150, Ö ñ after with tively CULASS ы П μ used н S in, loading, i.e the months 180, rt ſ۵, ٠ ince taken iment, ю Ч ñ, rt one loading. 130 For с† 0 ٠ earlie in initial H1 0 H nost load ψ 210 The s t e arri the after the measureme 7, different Ű • ø 4 ĥţ 0 270; initial loading analysis step when n H ٠ verage period. 28, loading Ч βı rt t h e اللہ۔ ج loading, the with the the 365 ູ , 06 Ľ creep it N number analysis, 7, w loading 0 1 0 was 180, load 0 H equili 5 4 5 the A t closer 12, and defle shown Ø ÷ N displacement was 270 0 ach T TO 730 17 for Ħ -3 -4 shrinkage ages μ. • • n с 9 , and 9 appli time time tions, rt 365, and 22, ы. С ወ Beam ration and н О time 17] |--H **و ا** ր Մ S intervals 28 545, ģ X 9 rt ω H D Ψ. ø • £ taxes in Ð ש' 0 (A ş.e. œ and a IJ 40, rt v ¢ ratio analysis teps action day ні 0 Н ф Н ٠ 1 1 1 U1 730 נים ו X • ω v ١Ū

rt Оке مسو H 0 ω Ω × Q, ٢t ភេទ 50 ò μ. ö 5 H υī ω ũ 'n H. D. ø <u>د ،</u> ŝ ~1 ρ, ſ۵, μ. H. U1 Ø n  $\circ$ , ທ ປ ø Δ Φ H μ. Ъ, 1 Εħ t s d Ð Q 5 ε ဂူ spondin N dat coeffi rt N ŝ • ወ NOT. Ħ H age H ω ø ա Բrt 0 μ Ń imental • Ø 14. ¥as ω Ū :1 IJ 0 Hh G σ ŝ cients S rt c† S F ω ώ μ. va⊥ ō с† 0 • were 9 3 Э μ, obtanied 0 0 0 5 concr data, ជ U1 ----days (J1 trj G Ø for ት አ О N reduced ٥, 7 ე х 0 0 5 ---0 the rt rh are loading hyperbolic თ ლ. (J . ወ Ъд 1 n prism. H ω7) μ. سو Ø Åq applying . ອີລີ ຮ Ð computed S ຸດ  $\boldsymbol{\sigma}$ 216 ω 0 n βυ ct ρ E Ö Ħ fact ù υī w ወ 0 N Usi 0 • ц Ц ί3. t-h • T S Q shrinkage th **....** ω ş..... Å ÖH 39), ы Ф the -----H Ø 0 later ե. Ծ 20 0 H 日 .0 0 11 11 method ы Thu s compressiv х rt. the 10-7 n ھىب than 157 value ŵ (3.44). function μ. **υ** ct ወ ਜ ~ 5 гħ ٠ ---ੱ the N ¢ ŧħ Φ ω **....** n HOw - 1 σ n Ω 0 Û ψ н rt ወ Ħ μ. თ ht († W Э H **√**0 Ø S ¢ ₹ α S μ. μ. Ω, н σ ы († w et o ه... H ወ • O ត្តិ 101 .727 0005 S rD н  $\mathfrak{O}$ used H II ເນ ເນ • ω 0 н g t ne Ф ω 0 0 Hh Т (i) . w ហ ஸ்

for Beam X3.

observed. ц р ing due н 8.5.g, esults 0 moments ст О Ηp N X variations creep . HON table years the due and 8.4, after to creep and shrinkage with time changes in deflections, reactions shrinkage 0 Ħ μ deflections, loading. summary are 0 Hi given. The experimental strains, following And reactions in Figs. and facts are theoretical and strains can 8.5.d plotted and bendс С rt 0

2 μ 101 с е ñ reasing Ξ loading A11 rate 30 8 t the changes 2 of the time due changes takes elapses ť creep after and shrinkage place. loading. вy σ OCCUT months рі 11

ъ markedly Ó sitive (2)Åq moment The the effects of region. presence creep 0 Ha compressive and shrinkage reinforcements 978 978 reduced ц Ц tbe

loading ω are Deflection greater than due the с† О creep immediate deflection and shrinkage 27 р С† years loading after

the n ¢, bution đ reased. the moment (4) 0 M maximum internal Midlength reaction is increased due to the redistriµ ct the maximum positive moment negative forces. moment } ø location N <u></u> result, μ. Μ location bending incre ased while 'n ۱۲. ۱۹ moment de-

Q gion n increase Ton reep -(S and Q0 greater 0 shrinkage much Compressive 4 1 1 2 8 than compressive the strain increase more than tensile strain of the in the 11 beam the increases negative positive strain moment does due moment rt 0 101 The re-

6) Theoretical results from the present analysis are

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the inhe rt H Hh Ω р С c†. 1th <u>ع</u> 5 0 N and number loading years rt. 0 Ωı HĮ. 귀 μ t ø α μ. Ø b H (D 5 Ĥ Fh. ъХ. ų. V ω rt ø Ø p, pendent 0 o **n** rt S D đ ĥ μ. n C н М († Xima 'ely 107 O. ¢, H vely present فسو ч У (A н ear 238 (A esults d H O ave ښو e n rt. hrinkag ø The QJ int M 0 Ih S xample Ś ው ትካ well rt rt. o S ω Ω ressive м р Н might ø H 1 m н H D D D μ н р **O** њ 0 Н ₽ Hi 0 H creep 0 H 0 H ä m œ. ore behavior elements Ø due М т Ф rt 0 H •• ω continuous 9 C 1 qualitatively, μ. ۵ بېر Ø цре loading rt the n. ù ñ the с Ю because ω # 100 rt เก p, the have and n ο ۹۹ rt ų, loading. ហ rt n and 8.5.h incr deflection, H qui 0 present reep 0 0 **....** ወ Φ creep æ maximum Φ 'n. shrinkage 0 m 11 been • اسو ancies shrinkage **O** 40 rt Ø e 9 2 6 0 14 н However 378 level and 4%, shows the æ ω beam ø satisf 479 6 and Ъ reinforced resulted due analytical The and 05 28 neg shrinkage analytical 0 U and ው የተ will total absence shrinkage tре • • 1 X 0 the 0 0 disc cannot 1† 0 0) rt 38\$ Ъ Ч d a t N 99 the tory considering 1. 4 4 6 Ø e s **O** midleng ы с С Fron time and ው rt μ, repancy reep S ent maxi experimental trai conc are mom 0 Hi Ю Ф briefly data, nodel þuð ന എ model. Ò. not nod p, and ч. 8 .mum φ. ົດ Э epen H (D) (T) used. iding 11 15 0 measur t t 5 Hi O F († distributions expe 0 Hi 0 |the rt 0 takin shrinkage tsođ ø 10 reac the ø dent disc рч С the continuo xperime the \*\* O. ,д (D 124 predi oted The ŝ quanti The თ tive rt. tion, unc й µ. g đ٩ ju, and σ us s rt 0 rt р. р. H @ S 0 H Ψ. e D **O** Ω. ₽. ហ ø н Ω. rt **n** ហ អ. c ω 2 ÷ e d laví Ĥ 5 נס 1 S Ð n d r† ø h noment the rt ដីទ rt ö b tativ the Q. Ω 1-h jua μ æ н ы Ц :tly ñ aintie rt H rt н μ. rt. rt ς. ወ value quali 0 50 Ľ, Φ Ø ø n in S 0 σ Մ Ծ Ĥ Ð ወ ď ient N о С H etwe n apω ancy N" ω n ົ 0 time .© ⊢h ወ а Н н. Э 0 Hi t, æ 0 († ŝ trai H. 101 ical ŧ ហ I. ø H Ľ

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the The the O (A) almost resultant tribution HOS tress LA. amount (Ť tensile ወ section nsile can identical. ы ct compressive 0 ር ወ force ŵ າ ກ rt is mostly compressive explained rain years is increased The reduction 50 1-1after loading is drastically and increased carried 0) 02 stress is markedly tensile follows. only slightly УQ Å 0 m forces the μ the compressive small Tensile tensile HOH amount reduced and the with Force concrete steel, ր տ time in changed. concrete already and the are since

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note

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8.5.i

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concrete

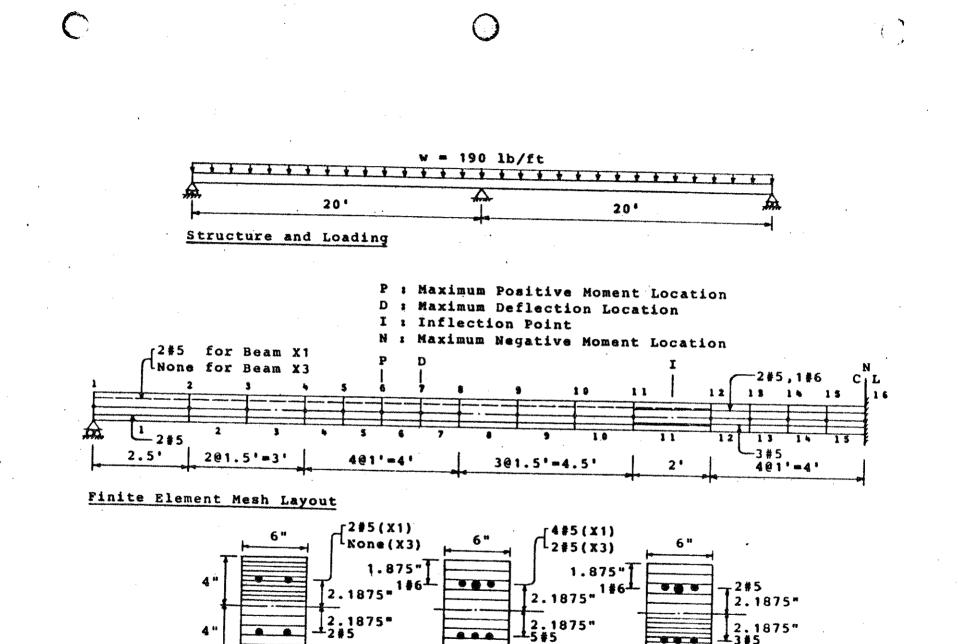
stress

019-

01 shi <u>у</u> tral D, due Ô U u U Ŵ í۵ ° × ŝ strain 8.5.h. only tensile e a m ō Ø 0 0 1001 m nsion ction . h t s t S B and æ compression side. years after ctively tt 0 xpected small ž axis level рі ст ×ω • toward the concrete creep ря († ×. **₽**8 9 D T S 10 10 FORCe compression and almost coincides location P where рı sustained compressive stress ው ርተ amount located between first nota that strain increase a t Analytical result of beyond the 10 10 loading loading the c.g.c. loading. carried 0 the takes that and This can be observed this Ω FT stress distributions c.g.c. is cracked, hence most ЪУ tensile The portion of tension side, locations the the with ≫ rt no compressive difference place on the the tensile years after 2<sup>3</sup>years after neutral **c**.g.c. the c.g.c. with time creep 'n and the compressive and axis ц, takes the neutral axis on concrete, and steel. the compression side loading the z г† 0 steel axcept will 0 m at loading concrete are loading the place, be true change the beam cross occur mainly shown Since њ 0 4 ₩. Ø for the present н. Н 0 11 0 beams most of the 1 n in Fig. and Can the neu-Fig.

The rat the line 5 ear conc tional Ω Û 5 F H 0 fact a presen stress distribution at 2½ years Ωı ٠ strain ĸ oncrete Another point ር† በ ő The This that creep 17 stress m B incorporation of this analyti stress the ₽. Ø (t), ն 11 intensity, **p**. stress higher resul worth obtained cal ۲. ۵ study computed ĊŦ. distribution noting in Fig. stress of the nonlinear р**у** but increases ¥as subtracting ດ ເວ levels nonlinear discuss ρι after function 94 († н. Ю 8.5.j is ø Q, loading рн rt 5 0 loading the creep effect 5 creep effect, i.e an increasing longer 0 H section non-mechanical լ... 09 the the despite almost propor mechan nonlinω • ω ц. Б Ł

nie the the As н р H The rev a S Ω N ١0 đ rt ١Q Пe 0 п 0 5 hown 0 c† Þ he rt ñ Ĥ. Ы ō n н 3 ñ. ۵ et ð t a l rt rt tion ወ ß moment in positive moment region is bending concrete are almost fact rsal Ð ທ ທ large compressive مسو ione Åq that result ц. Ц ທ ct and equilibri ο the 0 Њ **Hess** Ηŋ Â, тig. that the resultant compressive path with the ۰. the a increase concrete the oncre moment 0 1 nor Compr was neutral axis is located almost 8.5.j compressive this ease цщ t e steel assumed ō 1 1 • w 0 гъ 0 Hi has Нòн S redistribution iive 0 Hi Since 4. ە negative compressive strain, forces rt O initial modulus Beam X1. the identical is consistent force ct O increased b D the stress midlength follow н. П reduced to μ. compressive moment ល the carried The in concrete with 0 Hi the Уq CIOSS reaction. reduction region the μ 0) () straight-line decreased and maintaí large Åq shown the internal f ហ force e 0 tensile both נע רד 1 S rt, i o n compressive amount 5 the c.g.c 0 14 with the н. Э increased the carried comp ٠ accompa-Fig. the contine 010 forces The load horid u e H D 0 N 2.8 S ր. Տ н () | ທ А Д rt 0 ive and



Element 11

Elements 12 - 15

Fig. 8.5.a. Example 8.3.2 - Washa-Fluck Beam

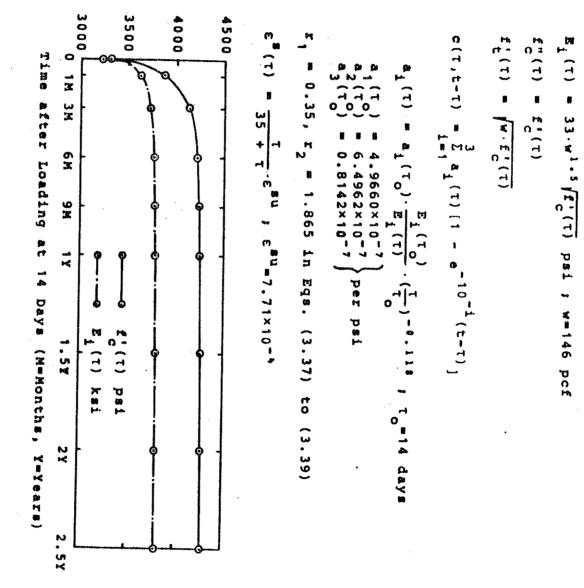
Elements 1 - 10

Cross Sections

Fig. 8.5.6. Example œ . ω N 1 Material Properties

Steel	f <sub>sy</sub> (psi)	E <sub>s1</sub> (psi)	E <sub>s2</sub> (psi)	ອ ສ
<b>#</b> 5 Bars	62.0×10 <sup>3</sup>	30.0×10	3.53×10 <sup>3</sup>	0.14
#6 Bars	56.2×10 <sup>3</sup>	30.0×10 <sup>6</sup>	2.01×10 <sup>5</sup>	0.18

9 Steel Properties



(a) Concrete Properties

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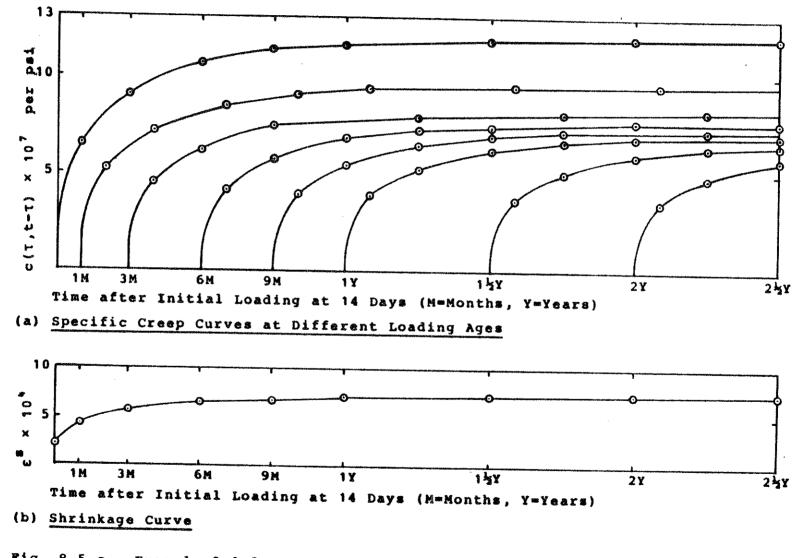


Fig. 8.5.c. Example 8.3.2 - Creep and Shrinkage Properties of Concrete

## Table 8.4. Example 8.3.2 and Theoretical Results Summary of Experimental

### (b) Strain E×10\* at Max. Negative Moment Location N

× 3	× 1	Туре	
Exp.	Exp. Th.		
112.50	-3.9 -2.47	At Loading	d # oU
- <b>9</b> - 9 9 - 99 9 - 99	-9.3 -8.59	After 25 Years E EC+ES	Comp. Steel Level
-5.6 -7.49	-5.4 -6.12	y Years EC+Es	Leve 1
6.7 6.84	7.0 6.78	At Loading	Tens.
9.0 10.01	8.00 0.00		Tens. Steel Level
2.3	1.0 1.22	E E EC+ES	Level

6 Strain EX10\* a t Max. Positive Moment Location P

×3	×	Веад Туре
Exp.	exp.	
-2.8	-2.2	Comp. At A Loading
-12.4 -12.17	-6.7 -6.70	
-9.6 -10.41	-4.5 -5.30	Steel Level After 2½ Years E E <sup>C</sup> +E <sup>S</sup>
4.6 5.60	4.1 5.65	Tens. At Loading
4.8 4.99	5.1 6.50	Steel After
0.2 -0.61	1.0 0.85	Level 25 Years EC+E

(d) Reaction R(1bs) at Midlength Support

Beab		> +	After 6	Months	After :	2½ Year
Type		Loading	큣	Inc.	ע	\$ Inc.
<b>K</b>	Exp.	4880	4990	2.2	4960	1.6
1	Th.	4828	4872	0.9	4872	9.0
× ۲	Exp.	4850	5050	4.1	5070	4.6
;	Th.	4836	5084	5.1	5118	ა ა დ

(a) Location 0

Deflection ð(in) р rt Max. Deflection

Xu Exp Th. 0.62 1.47 0.70 1.57 1.49 0.87

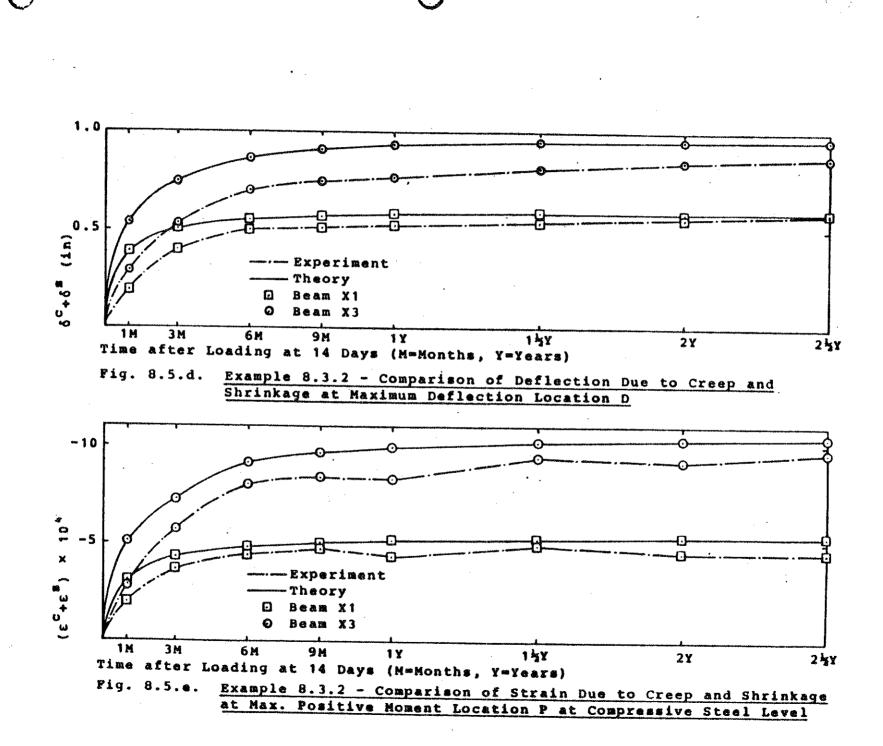
Loading 0.56 ¥ After 1.14 1.06 O1 ው Months 0.50 ភព+ភ្ន After 1.18 1.14 O, N 0.58 Years 5°+5ª

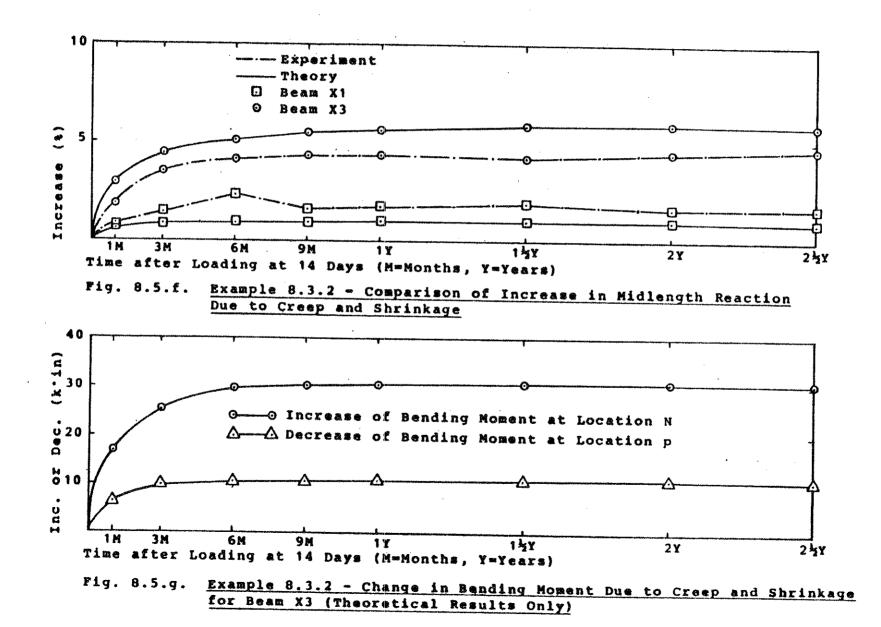
Beam

Type

XI

Exp.





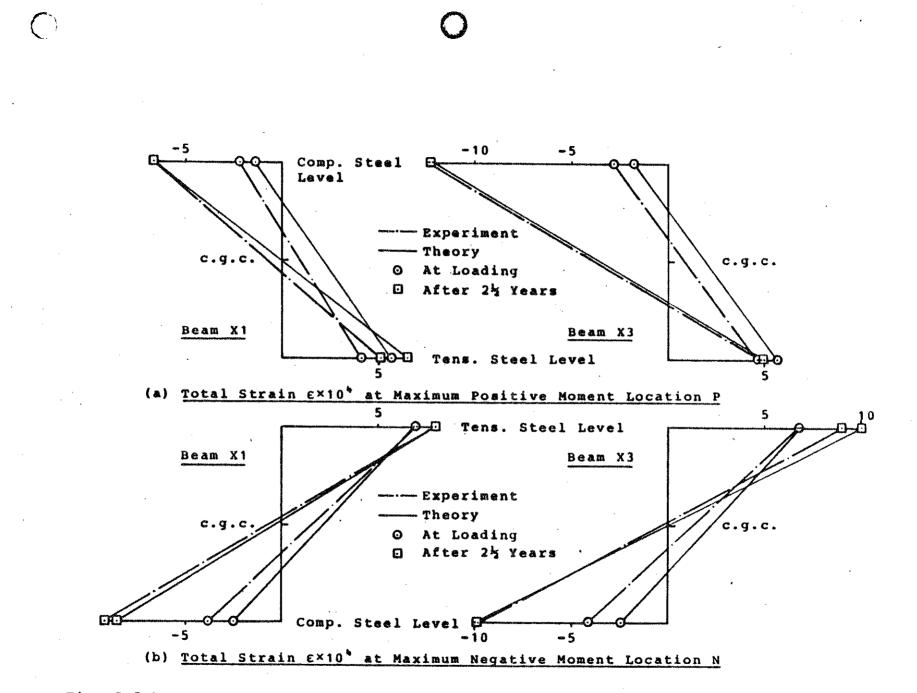
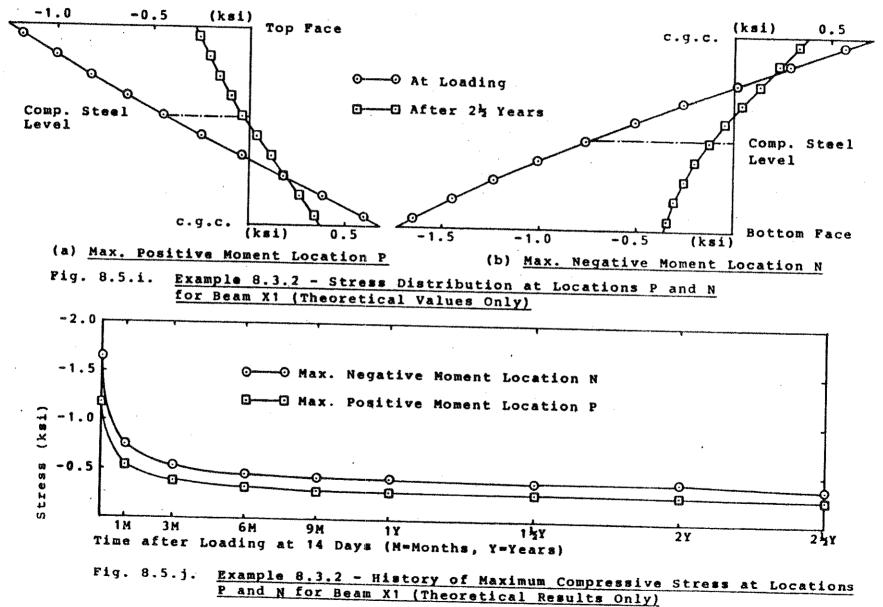


Fig. 8.5.h. Example 8.3.2 - Comparison of Experimental and Theoretical Strains



ω ct ŵ S increase r† n hown 5 train and ince ò trains Ø dt. 84 |--c.g.c. in the the strain  $\varepsilon(t)$ , as expressed e<sup>nm</sup>(t) 0 creep the с† 0 stress intensity, figure the stress is reduced which include strain increases compression the t D e face in Eqs. (2.1) at an increasing ն Մ creep corresponding mechanical 0 ħ þ the higher strain Cross rate е С rt 0 section Ĵ (2.3). rate from with from the ດ ທ the

## ω • **England-Ross** Beam 1 Temperature Dependent Creep and

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tur the neer concr stresses the biological shields of nuclear power stations are tions thermal ø increase IA examples. dependent. @ († @ . Many thermal that Shrinkage Analysis gradients. undergo changes due to the creep and shrinkage of reinforced concrete the However, 0 H stresses develop in these structures, creep and shrinkage of concrete Under the restraint temperature, but Creep it has Chimneys, and 0,5 shrinkage been widely reconized by ß structures are floor slabs under Flexurally Restrained Beam the of displacements generally relationship subjected are temper increase boilers, the a few of ₩-00 and engi-0 H not đ rotawith the يم 1

and on 0 S oncrete 0 0 н the 兄のめぬ einforced concrete obtained creep One ehfects 0 14 beams (76). the subjected 0 Hin earliest They temperature and tested structures was conducted by shrinkage đ experimental flexurally ىم dependent linear thermal curves and restrained creep р) († analytical different gradient. and shrinkage reinforced England studie temper-They 0

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Ωų r† F H ŵ n н anging from 20 deg n rt O 140 deg 0

ment Ե Ծ μ H Ø S р Ц  $\boldsymbol{\omega}$ gradient days . 110 110 )e a m ወ mains o ап, ų سر r† deg Ð H բ. Տ 10 թ. ശ p. after H Among ក ស տ Թ р t used constant n concrete selected ት. በ shown 0 and Dd t b e casting of t D e applied displace цц the bottom face laboratory in Fig. 8.6.a, is sealed the analysis. along layers. н 0 н by heating longitudinally. this and Dra concrete, the temperature study. unsealed length nt O 6 11 12 6 The when თ თ restrained 0 Ha The CFOSS beams с тор deg C. 110 110 the 0 Hi The reinforced face 16 section beam ւ 10 10 linear beап deg against 0 14 Since ted, only the n ы 10 temperature **.** unti conc <del>เม</del>ือ rt ហ լա Թ Իդ one р С beam divided bending **ا**سة r† H unse strai י 11 10 ₽ ជ ១ -(1) (1) (1) -0 -1 -1 6 Ω, فسبو b ወ μ

Ø the porated 1 n O Ħ mental cribed H (D arized the rt Ø beam The properties analysis. shrinkage ц Ц in detail With ы. М material Fіg assumed. 9 CL 1 ٠ 8.6.a. data following are used. 11 Uniform properties chapter shown Temperature ACI shrinkage specific 10 Temperature formulas ω used the <u>н</u>. dependent figure throughout creep н 0 Н the dependent tine tine analysis are function creep depe: used the ლ. თ experiare ndent ខ្ល depth of directly incor ը. Թ sum-003ŧ

$$c(\tau, t-\tau, T) = \sum_{i=1}^{3} a_i(\tau) [1 - e^{-10^{-i}\phi(T)}(t-\tau)]$$
(8.2)

arithmi Temperature lowing n function time shift curves obtained function HOT different fron ф(T) the ы М specific approximated temperatures creep Уd shown versus the н. Н folt log-Fig

8.6.5.

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ф(T) 11 e¢(T) \*\* ψ(T) M  $-T^{2}/2400$ ÷ 4T/30 I œ (8.3)

£ Ø different where note 7.18 t h e temperatures. 1. D close deg resemblance n and the reference of specific temperature creep Curves р. КЛ 8 0 н 0 1 deg 0

Ω ۵ age and concrete stress н the and considering the experimental result experiment, lat ŝ ٢t rete istributions . 0 esult tress, able e C on its specific Ross, present Ross t D e с Ф Experimental and are 8 . . . better than history concrete rt 0 are shown 15 present 150 analysis Experimental which shown together for comparison. նի († 11 βı Γt creep recovery and the effect 0 Fa days 80 stress, they Fig. the analytical result obtained by England ----steel stress is plotted. days creep. and it approximates analysis in. after casting of concrete. Can theoretical results used a 8.6.e. and 130 **0** 0 steel stress, from the strain and bending moment observed In Fig. and the analysis made by step-by-step method without days d o t 8.6.d, rt Ö after 1000 theoretical the 0 are very ۲.. ۵ history casting experimental The result Results of the plotted. summariz close In Fig. 0 m 01 K 0 steel 0 11 concrete Fros England the rt O 0 D tabu-007r r o ii いけちゅ œ • н. Б the и ta

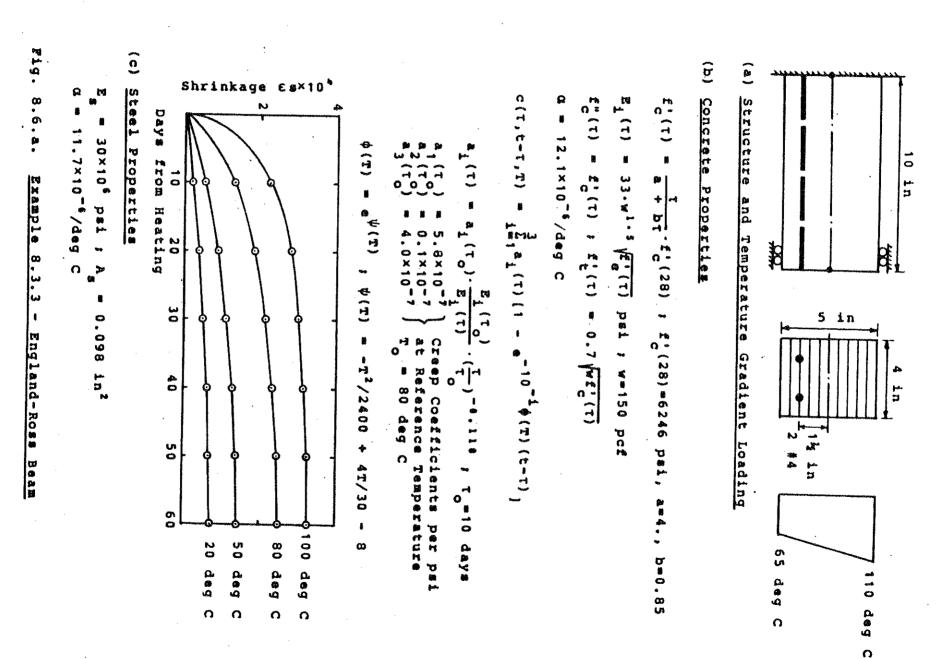
0 n place. days ct 0 Ö ē, the temperature The after and beam. The behavior tensile casting effect ≫ S gradient will be ĝu 0 Ha stress ы. Ю 0 result t'n e an equivalent concrete, flexurally develops compressive briefly discussed. shrinkage ĺp compressive restrained the stress concrete 0 develops concrete beam force since С У subjected in the acting takes ů, the 8 0

c†

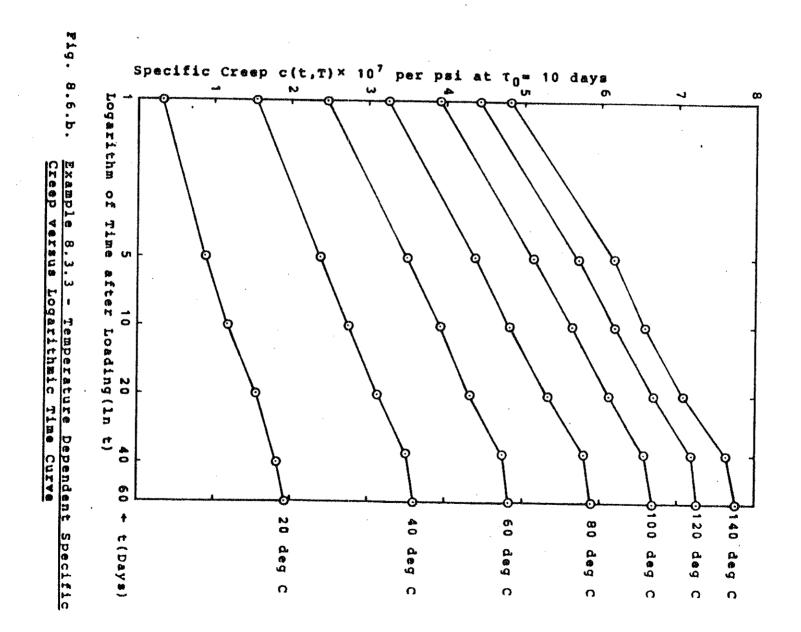
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O. р. H. r† As 00 tens ħħ а С e H 5 0 R Ø ຄ ĝ Ψ æ 41 plac ω shown ซิ ø ų H n n H . مۇ ω ወ н 0 V e d سر ď × 0 Ŵ 0 Ŵ UI. ement ŵ •• bend 1Ve Μh IA stress develops н. 13 t n e the տ Թ h 0 ñ Ч Ч S . Ĥ. 0 Hi ή μ. σ c† temperature O, à H O ው n 0 5 However, ٠ 29 the n .مو n თ ი ი (A) ր. տ will develops N beam Ð Ф , Ô 0 racked bend 2/5 in the since ю 1-ч. Э When ţIJ 0 H conc increased the ດ ເຈ the bending the the t n e lower Ω ave beam result. beam upper temper part downw due о Д par ø Ω. rt 0 0 ທ ກາ H Q t u The f rt H the the Ð restr μ. ſÞ 0 Hi Ħ 0 1 104 gra μ. over D н ct c†: p., õ D, ወ he թ թ. N ٤ H ρι j. . ภe B 95 QJ ¢ Ծ Ъ D 'n B й Н and r† D, rt р Ц а 11 lef ա. ស rt 1 1 1 0 rt th.

Shr Ô Q۵ m w ۵ ρ. i ng Я r† O. (J) ካ increases **C** ¢۵ dras Hh j. ۴. 11 :his ö evelo evelo H Ċ. rt. ø Ph read Le e Ĥ, ø Ĥ ŝ i nk the ወ (1) (1) (1) μ U the ດ ທ ທ ٠ O Siv N r† rt ίΩ Ø æ н 0 steel creep The 4 0 0 ğ Ŵ μ As ц Ц ģ r ed ¢, ້ດ. ຄ intensity maximum ц 0 р mentioned toward change creep 1. D Ín Çø 00 0 j. with this tre ຜ shows h н strain stributi нъ р the the tress esult conc 5 Ô. Ø the temperature due the strain stress rəddn Low 0 19. dis ۹۶ rt that ٠ H О. Н1 distribution would ወ becomes 50 0 increase , tt the it r ti c† n H 10% Note ø . the g. ы. М part a1so part due compressive redistribution the bution a beam, STRESS ٠ greatest that flexural 0 compressive creep ٠ 0 Hi 0 ⊁h H contribute 0 oreep and within Creep strain the the the tensile temperature. level 0 Hi the restraint p rt concrete stress beam. beam beam н. Ю concret the produce the top Сн СЛ since t o'p Ø () () 80 creep and đ ¥ A S ц. beam face great shown The amount the բ. Տ ø tensi compressive left this tensile STH 0) () face und an upward Thus proportion same μ. Ω 413 <u>p</u>u that time j.a. 1e n H n 5 н subjected ດ ເວ нg Fig. ы. М **ង** ភ្ល the ф П has (þ) Hi 08 († Φ Ő цре 0 æ rt. • elapse ወ H th řh. t 0 great S 0.0 0 1 and 0 0 Ø H 003bend سو مو 00 • thi o stre ወ S bend rt ten-G ď ወ C† თ G (A 110 မ က . ດ. н. 17 0 v ω ŝ ÷ ct



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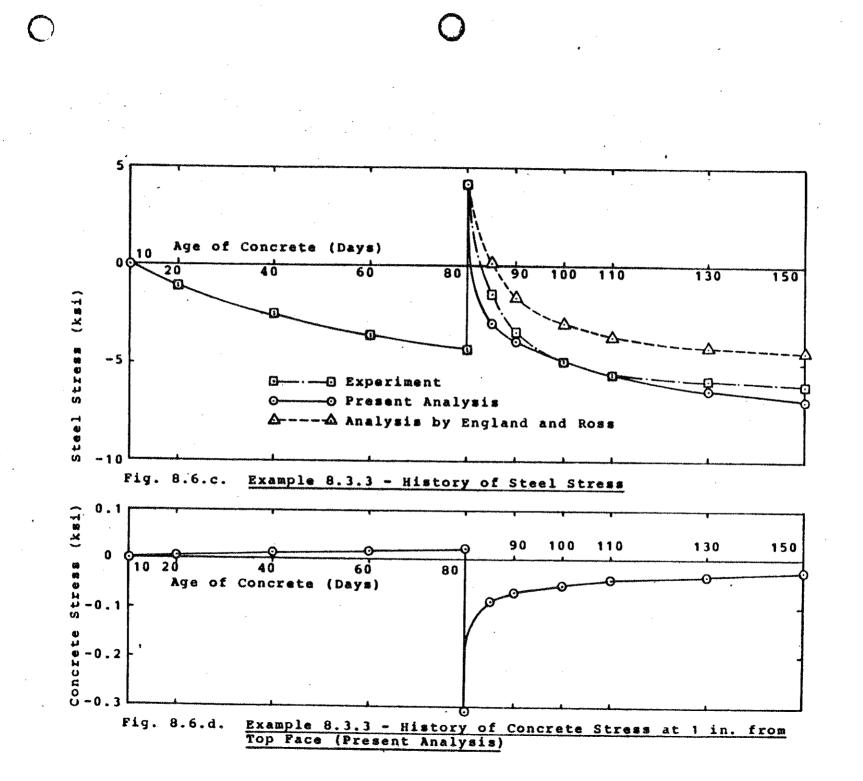


Table 8.5. Example 8.3.3 - Summary of Results

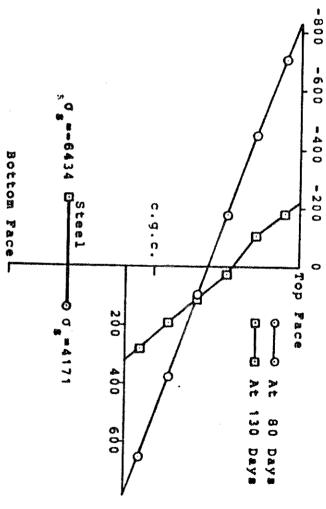
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Temperature Gradient Applied = 80 daya

. n n 44 Concrate Stress 92 († -call 1 2 from Top Face

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445		-25	-6992	-6100	150
463		-38	-6434	-5850	130
492		-42	-5565	-5490	110
515		-53	-4875	-4780	100
550		-68	-3819	-4310	06
581		. <del>-</del> 82	-2886	-1460	8 5
816	·	-310	4171	4200	
-146		21	-4366	-4200	89
-120		81	-3609	-3540	60
- 85 -		1 5	-2561	-2440	6
<b>.</b> - 3 <b>(</b>		5	-1017	-1220	20
b) E(Th) ×10 <sup>6</sup>	- <u>-</u>	0c(Th) (ps1)	σ <sub>s</sub> (Th) (psi)	0 <sub>8</sub> (Exp) (psi)	Age (days)
			1		

Fig. 00 • 0 • • . Example 8.3.3 - Stress Distribution at 80 Days and 130 Days (psi)



rt £Ť. above 50 emperature н. Н effects and Delow gradient are the Bore 0.9.0. ທ ມ. 0 H applied, as shown less have balanced comparable ц Ц values Fig. 8.6.e; and when tt De

н amount ф ф rt educed. tress σ 'n . 0 0 The reep ٠ the 0 m due reduction is Note ሪ ተተ ወ Ne Ne strain ц 0 Д The Creep с† О strain also N N that 9 C T fiber reduction strain redistribution թ. տ note which temperature both greatest 14 15 correspondingly 1. D since compressive and tensile subjected 0 Fh decreases t ne stress the on the dependence figure 14 stress rt Ö ດ ເວ concrete ა ლ д ф magnified the proportional the that concrete ۵. ۱ maximum 0 Hi creep 1100 եր. Մ μ concrete function 2 0 ratio shown stresses strain temperature the fiber t 0 0 m ц. Ц the creep largest н 1 0 m гig the 0 1 1 0 the

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#### ω ٠ \$ Prestressed Concrete Frames

œ 42 -Lin Beam ł Ultimate Load Analysis 0 Fi Q Posttensioned

prof the Fig the с† Ф М ٠ support. beams ወ ile, . Ц Ц 8.7.д. The 0 and structure and its m tested 11 12 0 consists The The Беап H 0 H continuous prestressing 0 († static 0 m 0 C 1 ρ material point straight beam loads are steel ե. Տ where part which properties symmetric tendon selected the concentrated has about for 00 H C extends þ concordant shown this its cenh r o s load study 1. 1

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and н Beam reinforced. tendon μ. ne ne S applie pre the B н. М consists stressing CIOSS Â reinforced • and One section о њ ω steel half curved <u>م</u> with ω N 0 ff н. Ю tendon parallel wires divided the beam דים לי mild rt ր. Տ over steel also into ր. թ the analyzed with bars divided 10 0 H cen concrete while 0.196 ter into suppor н. Л. Beam layers. **1**0 --0 diameter. r† ≫ seg element н-И The not

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ω ct moment compared to ο c† tax the łħ H two 8.7.c. are 0 Mh than 50 0 H 0 H 'n Ē. n e rt the () () the ø Ô. н Р н load ing rate Béam results tabulated. the H D rt 14 0 place, the cracking, load midspan region, steel, Although the analytical values table 8.7.(a) experimental values, excellent о н 2 carrying of the the ц. Ц can thus increase the the deflection t D e rate a s 0 0 These end the internal forces capacity. positive moment shown results rate noted. addition of mild prior to the cracking. O Hì reaction to the values are plotted in Fig. 8.7.b and becomes the in Fig. and the end reaction due experimental H O H Due bending After Beam nt 0 smaller. 0 T 0 8.7.c. the the the region becomes greater W moment applied redistributed such steel bars increases аге presence 9 7 Q and cracking comparison stiffer Correspondingly, with slightly analytical load H D 0 H ц р е ц р е 0 Hi the t De increases than those between ő concrete negative increase stiffer values reinload that

With S ω 9 4 average н analyzed rt ct. CT. Ö howed elatively crude mesh 0 D þ aken. . а П N kips. ц Н the 801X ր, 0 10 ۲ بر failure number of with the nate n ե Ծ displacement rmining The HOR rt 0 load. Веат ultimate 0 H ы average load increment 4 1 1 8 ll iterations per load step Beam A and 45.8 kips ယ ပာ Thus exact increment ratio layout kips, load measured Þ the ው rt values and 40 and large structure kips Beam 0 11 for and ц. Ц Ø the tolerance ի։ Ն load Beam **}-**+-0 9 1 1 9 Beam 'n cracking h analyzed with analyzed Nas ς'n . ω experiment increments W kips, თ • ου ct 0 The analysis load ֆ Մ មឹ Веап 0.02, kips. đ x a s and are ρ Þ the 'n ы. М li

555 μ σ Ħ S ω Ω. O Ŵ 0 łħ and E 0 lax (D) r† 0 0 Ó H ¢, 0 oncr hown Ō -h h **بر**ز đ Ø Ô H ល E. 5 μ. μ. 0 ١Û đ rt . 1 1 1 1 سو ω rt 0 . Бе ¥. negative 5 0 ٠W n 0 5 ø Ð, ρ., lmos н n e L C C v В j.s. oncr rt 4 due can rt H Ø maxi ø Ħ maximum grea оd ١0 rt S) et r rt hŋ rt O analytic ٥, ñ Φ şī. ø in the the rt 0 H . 8 9 8 9 đ rt S σ Ð ů. n տ 0 ō ¢ فسؤ mild moment Ŵ and . Ve Э 1n o t ю Ф ŧл со • posi ате negative ወ same rt. ц Д in ccentricity H -1 momen 2 ed n . steel ٠ рно оно S Ø only .tiv in n ው rt ≯ t ល ស rt βJ ₽hj loca N 'n. ¢ 0 ወ tre rt Ĥ ø bar both 947 d ល -ወ 100 poth slightly ŝ H moment bend tions раг ssing ij P (A maximum plott 0 distributions atio 0 m ທ ing locati но И Н beams ው ተን steeper compared ٠ n E the 0 0, Beam 11 ٠ momen different Ы The ons ø negativ سر H0 利 tendon 15 ω rt ta 1 ω ы 0 rt incre dif since conc 1000 can ր. ն rt H and ο ø р rt n compre ۲h rt μ (J) compared ٠ Φ н 0 Ħ **D#** grea ወ ø ወ H Ψ α μ ٥, ø the nonent ň ω Ø ወ S maximum ወ Е Þ D E S 11 S 0) H 1 ng ter rt. rt. ο 0 Þ S ល rt ա Մ th ø ы ά, ທ ພ. n 0 U Çø H H n **U** and سو H D 1 4 d r x ወ ወ ω ŵ than t F S ወ rt j.... ŝ -Ħ а Н p. 0 ò ŵ. 0 0 ω rt 0 Ô. **G** UN, H ā Ħ Ø rt ρ, ជ O ወ ο rt н ū ø ation Ηħ n d P a t X H O H аге e D N н цe μ. istri ein-Ċ. rt that buts n tive н. n ۲ħ the н 0 1 ŝ S 7h || Ł

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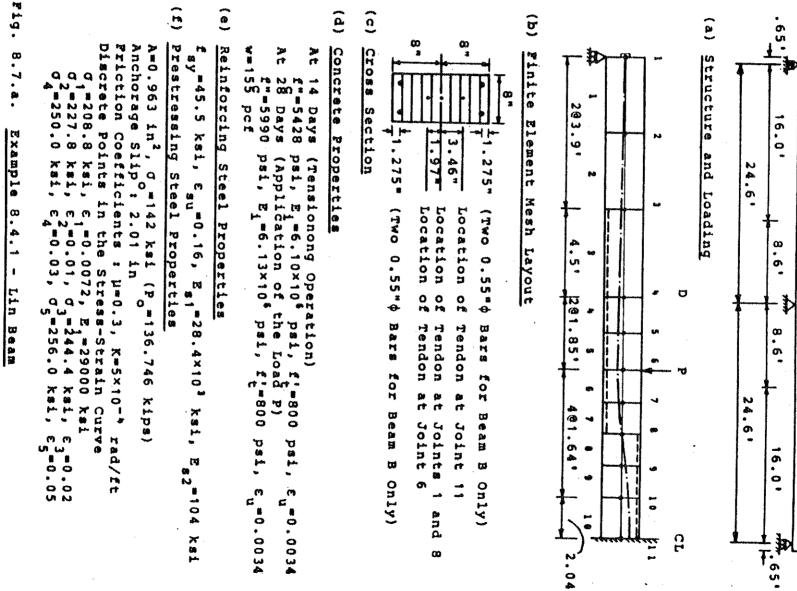
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50 **Q** 0 0 Ø н H ω 1.5 H 1h ω c† ወ ወ • õ ø Ħ rt () 75 ~ ated QJ Ø **j.**.. ወ Ъ, H . c† o B rt. rt IN Թ ೧ ወ <u>b</u> 50 Ö. H ហ ١Ņ н ወ rt ወ ο ហ ş.a. μ. 5 д н řħ farther than N 5 0 vely and rt ſĎ with t t t e н ц ц ŧŋ; n c† plotted ω ¢ ٠ н tha S ø ø tendon maxi ເກ ເຈ the Ś Since apart . et μ. ¥., ដ្ឋ нон н С incre т Б 3 μ. ທ et within 417.0 0 Ħ the sođ from. ი ი Φ ы Ч 0 |-igme ø tend in μ. ų. μ. Ø н Н. ρ, 477 B Ë 0 5 0 rt 5 **r**t 0 4 တ H Ó гħ 0 ٠ N 0 Ø ø Ħ 1 ő load 0 + and ։ Դ ω O T O ր. Մ ທ ທ ф • ы ហ o a bond S 0 ង ā C H ٠ (I) n 0 0 ٢ħ j.... 0 H Q and -1 1 0 0 0 w rt ω gments ր. տ enti-5 6 D rt s O ive tabu the БĎ with ເດ ເວ S o B rt gmen e J н nome No. ٠ ω ы В absolute rt. μ. IJ n £Ť No. rt нЭ ο Ħ n រះ ល ω Ħ ct un Q,  $\mathbf{z}$ rt o o н a D 3.0. • ດ ò 3 н. П rt  $\mathbf{O}$ 5 rt £ 0 وليس 0 Ð P Ω, († value  $\circ$ **рн**. H. فس rt. ρ ហ n 5 ۳. 0  $\dot{\sigma}$ 5 ០ ភ្លេស ស ա. տ ω ----() 1 æ ወ ø

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ö	Q	ω	7	6	5	•	w	N	-	(%)	(in)		
121.56	121.58	121.62	121.68	121.78	121.84	121.85	121.86	121.88	121.90	1.264	-0.059	14 Days	Веа
120.49	121.01	121.57	121.53	121.34	121.38	121.53	121.69	121.81	121.85	1.266	-0.099	28 Days	am A
121.56	121.58	121.62	121.68	121.78	121.84	121.85	121.86	121.88	121.90	1.255	-0.052	14 Days	Bea
120.74	121.18	121.64	121.62	121.49	121.53	121.65	121.78	121.81	121.85	1.259	-0.086	28 Days	8

## Table 8.6. Example 8.4.1 - Summary of Analytical Results Before Loading

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Table 8.7. Example 8.4.1 -Summary of Results Due to Loading

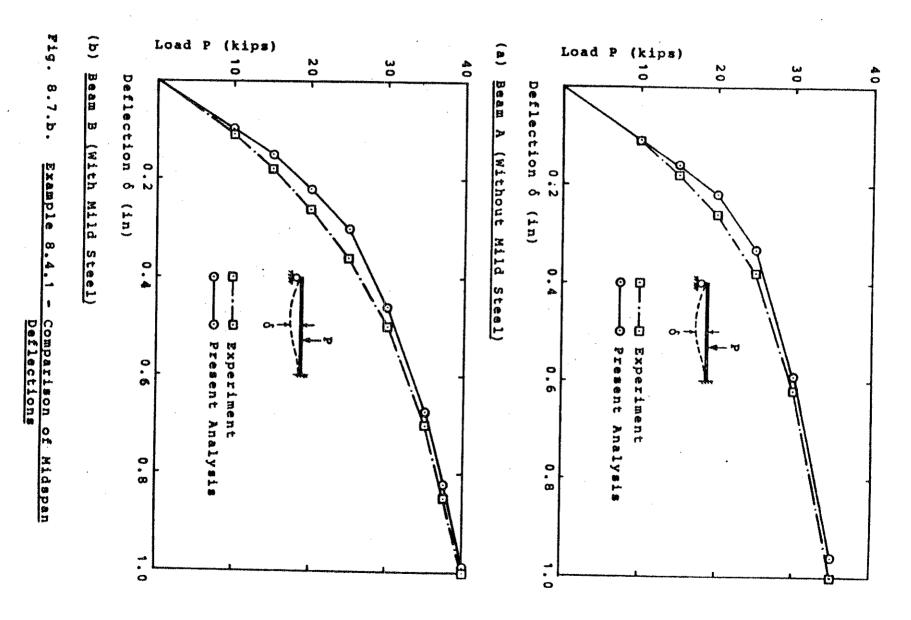
1

# (d) Variations of Prestressing Steel Stresses Positive and Negative Moment Locations at Max.

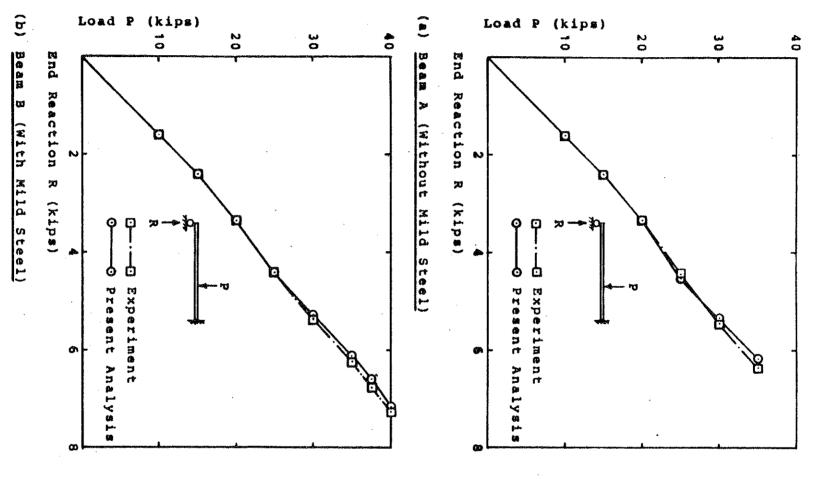
1	T	T	T	T	1	7	T	1	1	-	-
•0	37.5	35	30	25	20		õ	0	(kips)Stres (ksi)	5 d 1 1 1	4 ) )
		154.8	138.6	125.9	123.2	122.7	122.3	121.4	Stress (ksi)	Веал	
	ļ	27.5	14.2	3.7		+ .	0.7		Inc.		
145.0	140.9	137.6	130.9	124.4	123.1	122.7	122.3	121.5	Stres: (Xsi)	80.0	egzent
19.3	15.9	13.2	7.7	2.4	1.3	1.0	0.7		* Inc. (%)	8	цл ,
I	1	178.9	153.6	134.3	126.4	124.1	122.9	120.5	Stress (kai)		
I	l	48.0	27.2	11.3	4.9	3.0	2.0		Inc.	<b>A H A</b>	P.S. S
173.5	163.9	153.6	142.2	131.4	126.3	124.1	123.0	120.7	Stress (ksi)	00 00	egment
43.4	35 <u>,</u> 5	27.1	17.7	8.8	4.6	2.8	1.9		Inc.	an B	10

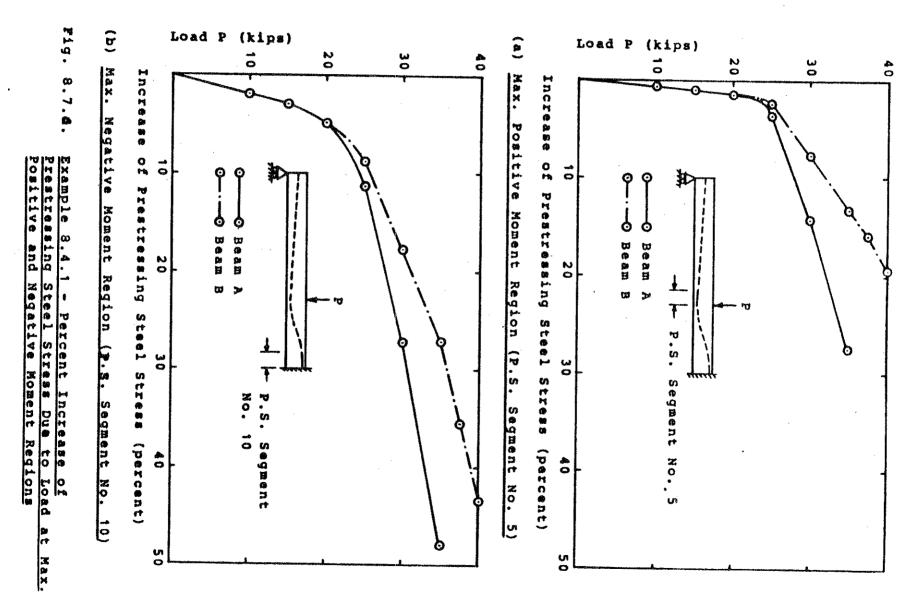
(2) Comparison of Midspan Deflections and End Reactions

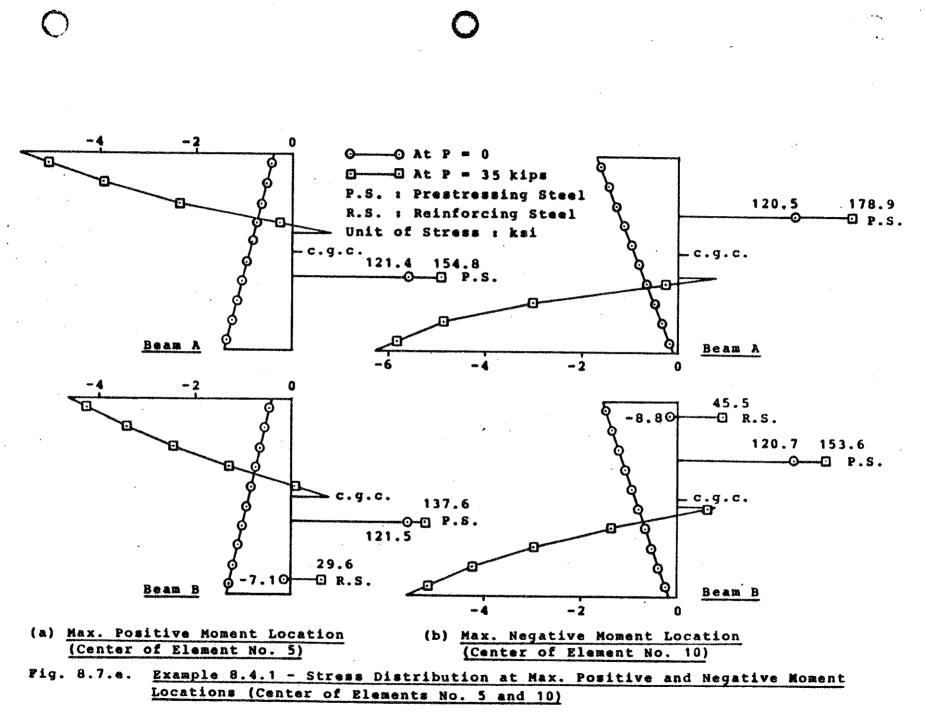
40	37.5	۵ ۲	30	25	20	15	10	(%1)	- 10	Load
	1	1.00	0.62	0.38	0.26	0.18	0.11	Exp.	Be	Midspan
1		0.96	0.59	0.33	0.22	0.16	0.11	Th.	an A	oan Def
1.00	0.85	0.70	0.50	0.36	0.26	0.18	0.11	Exp.	800	lection
0.99	0.82	0.67	0.46	0.30	0.22	0.15	0.10	75.	8 8	on (in)
		6.35	5.43	4.43	3 . 35	2.39	1.61	Exp.	Beam	End
l		6.17	5 - 3 4	4.49	3.34	2.43	1.62	Th.	ä ≻	l Reaction
7.26	6.74	6.22	5.37	4.43	3.34	2.39	1.61	Exp.	3 e e e	
7.15	6.59	6.12	5.29	4.40	3 • 3 3	2.42	1.61	72.	13 13 13	(kips)











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into ц. П are ъ ά ture roperties resent the used ---4н. 0 Among experiment. analytical study. concrete divided into H O M are t De the shown beams three layers. The 1 1 1 10 tested, locations I-shaped cross Fig. 8.8.a. elements. The Beam structure where 14-5 Closer One section strains եր ն half and element selected i ts 0 F is divided were the strucmaterial divisions for measured the

Б bution ţ. Experimental square section a F eam rt r† 0 0.5f-Ŗ H D e casting 0 |-method 8.3.1 initial assumed Creep shrinkage based ր. տ based coefficients modulus computed to be uniform throughout 0 1 0 0 the values eut () Hij Уd secant given กา เวา (1) ¢, are are procedure lightweight experimental generated modulus also used, described tr) the by the concre Ņ and its 2.95 сгеер depth 17 0 leastx μŗ CUIVE. 106 0 Hi distri-90 617 the the ---- Þ d s đay

ity after linearly in the The casting prestressing toward midspan 0 m supports. concrete region, steel with and The tendon the the prestress eccentricity has initial <u>p</u> ņ Pi constant prestressing released decreases 0 0 **O** entricday force,

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μ perimental and rt e d compared H **ب** midspan 0 n Å, φ ω ц ц н Ф Ū, þ. TT. õ esul rt tained H h. • Ø Ø ain table ical ſ† pred ement in Fig. 180 57 (0 i n rt M Ten μ н ς. Lot camber can t b e đ results ው ő уq 8 • 8 300 time with 'n midspan results. n p μ g\*8\*P Ծ Թ those reference Sinno • n days ው values steps the and observed to The 0 н 0 Н ħ and ρ rt ដួ and μ t b e the experimental predicted values H the were taken rt 1-1midspan. đ Present D 116 ω • Furr bres н prestress 8 0 the 300 camber, release ₩0 ₩ rt by 0 0 N O N days figure respectively. analytical Beam the 11 ŝ ног ٠ н prestress good agreement and ወ after loss H a t e Lns The ហ 14-5 the р Н Ф H Ø rt v ው rt Ŵ experimental present • 0 Ha present ۰. relea ρ 10, taken soluti 'n location Both analytical creep loss Po The ່ທ ເປັ ----õ σ QJ o p the fron • et. are and analysis, with the exexperiment i on method. N show 0 ш resul and 'n the 4 1 1 6 tabulat are ω Ο Э pett ¥ ę, rt total ana Ħ plot-40 The ⊢ ∙ 0 ρ, 0 H ju M ø 1 ÷ W Ω,

d u e ρ ø Q sho and . د ا µ ₽ 10 e H iA nalys xperiment ā rt ŝ н н n p..... t 0 than it Ha teni eleased Ħ rt Tine .≺e in μ. H the Ŵ ø b D dead lease show moment 9 C 1 dependent 0 Hi shows creep the load. dead Ŵ conc will هب. beam N • produced by and load 28 H P 0 0 -1 ct Ø some of variations ы Н. 5 shrinkage briefly moment. and ທ ທ 1055 subjected ø t ne rt the 0 Hi 9 1 1 9 midspa discussed. 0 prestress, beam 0 Fi prestress FOR eccentric the the conc ٦ the bends H P camber eccentric Th present ct Ø Ø and ነ የ compression upwa When and 10 and Ń lost Ø the н Ц the the compression ω example rt. t D e sinc due ซ the H P S σ н N e S Ø pre ወ laxat ent t 0 **}-4**+ the - 0 - 1 1 1 1 1 Ŵ 'n the H Ŵ the -67q ወ tress រ ខ្ល 10 n

مبر S pan arg ø н μ. S bend ŝ М ወ ş.... ω b d ሰተ መ Ĥ. S train than t F ወ ۳ 0 S ŝ ω r† o 5 ø H. щ ò n ρ c† μ., 0 Ľ n ρ. ¢ ወ ct 0 rt р е

and and O t/) rt resul Τh rt H 0 н. н þ Ĥ train (A) ດ Ø Ø 0 ø Ô Þ n Ω. the the ð ъ n ΰ ወ ct ທ ō 0 0 H 0 F B Due ş.... a H э С а |--'n also 1 1 **O** relaxat the . ທ O н ω an and amber Ø sed, rt. N 0 the sive increas цпс increase compr rt the 9 1 which increase . مبغ ju. 100 'n ò n compres ž <del>سر</del> et: essive decreased (A ρ. н Ð 0 Fi ø H æ S Ŵ ŝ, μ. S 0 Њ ወ S the 3 the n rt toward լ. Մ turn sive of the the stres മ camber prestre the rt dec COLL camber. the creep the ú smallest camber. through rease 104 due ø botto spondingly Ø 0 Hi Ø et. decreases 9 a ő 'n Shrinkage O the Ħ onc face. the the at the 0 The н camber e te the depth uneven net t op the Hence the о њ σ effe )eam; 0 15 pres fac concr dist 5 H () () () However Ω the the ۲b rt ወ tress М rt Ø μ. 0 0 μ. н rt D ħ Ô. creep H Ъ Ծ Բ տ տ ō the am. ţ0 ወ Ω,

and 1nc Å the G the above n 50 0 1 O ъ **O** n Hee 100 õ Ö rt H G æ H E rease Ś μ. n ŵ a 0 **O** midsp e d camber ď ካ (C) n HO 8 1 Ω ø urve The ø rt Ø mentioned CUIVe urve takes with N t 0 н ati Å pi rt an mos t t B With and has • This 00 the 300 . . . . camber place time shrinka dominant place the the H similar 0 H can present days proper ц С <u>ĝ</u> t b prestress incre rt creep ge decreasing be observed after ру ō an earlier ties ህ curve properties offect analysis. 100 ase μ O curve days release 1 ው rt Ŷţ. 1035 and С С С Thus, 05 • ω <u>1 n</u> Ø a Fi n T period the the loss The since after days ter which most the The ы 10shape relaxation camber <u>.</u> rele рн ct experimental р Нъ and similarity t be 87 0 Fh release large et mìdspan n H ase. н. Н the 0 H the н. 8 shapes release the amount 17 9 17 rat the incr Can CUIVE The <u>p</u>i experiment אק 0 Fh H 0 11 0 H 0 ø n and 0 0 a s e ratio of Fh. Ø 0 н с† О 0 f† ø s tres f inhave the 50 ħ ø 000-Η Д the æ **D** 15 the 50-cam-0 æ Ø ht a s e

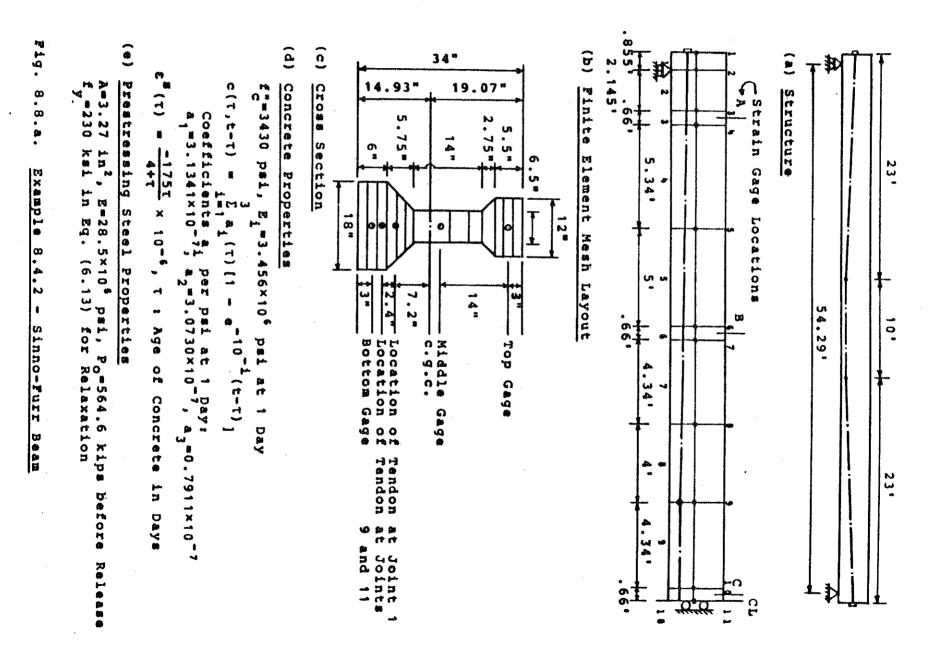


Table 8.8. Example 8.4.2 - Summary of Results at Midspan

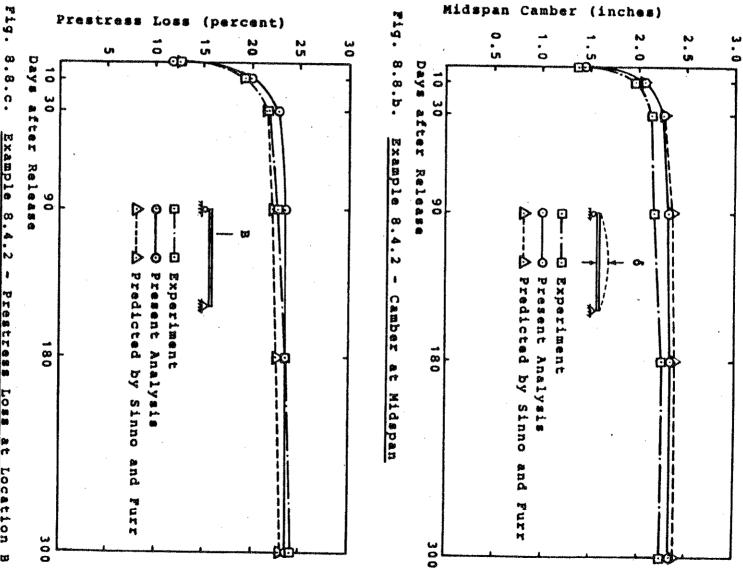
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1470	1380	1315	1210	770	006	820	780	700	& - 	290	250	240	190	75	22.65	21.03	20.43	18.57	11.73	2.11	2.06	1.98	1.82	1.33	Values	
1508	1482	1421	1290	783	881	863	823	736	413	255	244	224	183	40	23.11	22.75	21.81	19.77	11.99	2.35	2.32	2.24	2.06	یہ ب بن	Values	
2-6	7.4	<b>0</b>	6.6		-2.1	5.2	נז גי יא	U1	-0.5	-12.1	-2.4	-6.7	-3.7	-46.7	2.0	8.2	6.8	6.5	2.2	11.4	12.6	13.1	13.2	0 0	& Error	
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-		•	<b>4</b> .0		-1.2	6.	æ 	9	- 2 . 4	• 3.	8 • 0	4.6	2.6	-64.0	80 • 80	15.0	15.5		<b>4</b> .3	11.4	12.1	15.2	12.1	89 . u	* Error	

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8.8. 0.0. Example 8.4 N . Prestress Loss at Location B

days сі Н п П et. 5 n 0.80 1 ω 5 ñ rh. H Ø CŤ. (0) Fil and ases release 0.91, н. Б t ne 919 respectively. camber comparable and the ¢, H t prestress the ր. Տ also values n 0 loss 6 D, g, c† М ρ noted ét elease 300 that

#### 00 w Breckenridge-Bugg Beam ŧ Time Dependent Analys μ. S 0

1

5 ω Η bonded tensioned μ K eckenridge S **a** 1 e Among and Pos analyzed with n unbonded 94 tensioned and series two Bugg т 0 н 1.25 inch diameter beams 0 Bonded •the (117) up post-tensioned having present and t 0 an Unbonded study. œ н years simple high-strength CTOSS after simple section beams loading, Beams tested and D steel postр А

0 0 0 lar ø 4 0 tively from 11 ded. stressing near layers. concrete concrete Ô centricities foot correspond CTOSS 170 776 The span support Two layers. layers structure St80] section segments beam prestressing 0 1 elsewhere. n 0 and segments. region and they €. 94 11 20, the ω ۲. ۱ н 0 н 1 1 2 6 #÷ ω 477 947 divided starting element shown 1 2 8 bars ы support stee 1 Cross lower Segment ビュCカ ц Ц р Н П into numbers from the end support. Fig. 8.9.a. tendon is divided section tandons modeled tendon are numbered 0 7 0 regions 5 numbers straight with elements. in which have Åq թ. տ ۲. ۱۳۰ н 0 4 divided Ĵ One divided ¢, reinforcing the upper curved they half The 1 n t o into constant 9 I D ou u ț rectangu-0 consecuprofile **5**0 \_\_ ហ the embedtensteel 20 pre-

summarized 50 rt rength ø xperiment. 7ne and material 1-1-4 1 2 0 ng. 715 e modulus properties .9.5. tensile 0 Hi The concrete utilized strength variation With Ļ1 1 н. М 11 17 0 assumed of the 8 A 1 1 1 analysis ы. ФЛ compressiv H O H measured t ne a 7 e ana-5

**f**†

U)

ст 5 Ф trs stand lysis. age humidity computed у С nenbor method. ω μ ct. assumed ູດ ເວ w .... 0 7, (T) shown hyperbolic years dividing analysis. H loading ard ACI creep (2.19) and H +3 Since Ø based рс; based on ы 10 • H days, when the prestress was ä Ъ р. Н. age ы 1 1 다. 다. 738, (3.44) function the 0 12 Fig. н р р (2.20) Later (2.18) 11 17 8 experimental the following slump ultimate data given 8.9.a were computed was used for the creep coefficients average specific in which the than' 8 ¥ a s УQ ы ж ... ... Ξ<sub>1</sub>(τ). 2.01. стеер experimental shrinkage days. н. Э стеер creep curve experimental in, minimum section coefficient 1 1 1 0 0 1 1 0 Then, ultimate shrinkage data Shrinkage correction applied, У С 4 1 1 0 2.2.3 ப. ப 17 0 14 0 1 1 1 0 thickness creep ц 10 1 data ۵ ۴ 2 9 X was 0 1 1 leastvas diven, Conputed factors were coefficients •\* simulated used loading average obtained data square 0 m esu 0 11 11 ц. Д н 0 1 t n e U V F 0 F ¥as с С

0 1 1 conc beam. Ô. sdtx entrated けどつ N010. ٠ 0 1 1 1 ≫ רו tendons, and the Deam live load was ----474 ម ម ជ ម ព days ¥a s initial post-tensioned 8 ft ft 8 ft prestressing applied the total transfer dead a t 0 9 two load œ 10100 0 111 days quarter prestress, 0 m •0 after 0 the beam 2 A V points 197 casti t ne 2 G X א ע ע р С O Fh 0074 9.47 0 10 11 1 1 1 0 0

14 0 14 U Unbonded lysis e Fi onded 0 m three The 2 0 S prestress with and Deam inalysis load performed unbonded was Cases analyzed ¥ 4 5 т 0 Н beams \*\* ----မာ performed 4 a D 0 1 1 time steps. 80×0 10 11 1.0P and 1.5P, where unbonded 1.02. different ក ប đ beam, 4 Bonded Since ycars a 5 in which 9 C 1) 9 C 1) additional beım 9 E t o r ۲đ shrinkage ų £ L L S the the .... ហ analyzed Ð anatrans 5 0,4 X 0 m

m

9.0. beam. FOR р Ф Г large served. midspan +-ATT (n experiment average s Ú) nstantaneous ¥... Ò ;; (n Ð ĥ ø ø inkage other are • 0 m н n load, the Summary ¥ deflec 1.96 good deflection 0 Њ t ne given With cases, data and s † u 1 н 0 н key tion 0 њ agreement the deflection ր. Ե analysis н 0 1 ratio values ratio the 0 11 11 t ne table Same HOR N 14 0 H 9 C 1 mídspan experiment, ratio of the HOT the shrinkage between between 8 9 the bonded due unbonded The different bonded 0 m deflection 7-year rt D FOr 4176 1710 experimental beam the loading and data, the beam 7-year beam camber experiment was 1.91 Cases tt¥0 bonded and analysis used ј.... (л compared results |---切 deflecti н 0 1 с**т** н. Кл plotted and compared t b e **4**00 bean 2.39 the њ 0 ң the and analytical deop 045 shows rt Ö without 0 initial camcomparison. analysis. 5 14 т О the Ð arison the 0 D rt n rj∔g. Ò slightly H T O both analy-0 the bonded the 0 က •

ជ ព ព U 4 1 2 8 segmen TXPE O. and Segment unbonded beam with ٥, 0110 ET H 0 e s s onded rt. . 8 2 8 s C p. Dres Serv H H ۳J rt L: Ô P., along gment ji. ģ 1055 14 0 14 , t ω tress beam, beam ω r F بب. دم 00 • ٠ and segment 45 6 20 9. 0 with located near Thus, <u>با</u> with t n e is located 1.0P. N O length shows negligible 1198 H the change オゴの epresent 20 Fig. 5 t ne 0 M 0 f f 0 C t н 0 н sane segments at midspan and each t) 0 1 2 analytical 8.9.0 ц Ц Ц Ц 101 shrinkage 1 2 0 the 0 support bonded tendon. segment average shows prestress bending ω and result and data beam. the ω values N 0 Thus, on the ាឧទ while close ₩. 86 р; (а results 17 0 14 (A the However н 0 1 the tлe evenly t n e нь 0 11 the to the variation larges t h e results bonded the н 0 4 bonded ¢ ÷ <u>р</u> р Ч F F O O T 10 17 **c.g.c.** upper strithe et . beam. Ф () † ο the FOH ր. Մ m

50 57 57 r ω 50 1 1 1 1 1 1 1 i i i Lower 1.0P and 0 7 Q tendon, 17 17 B plotted in Fig. 8.9.f. SCHESS respectively. թ. Ռ mídspan т 0 ң Variations 4 1 1 6 bonded н. П the beam total with

dead average riction. ompared 5000 load During ₩. initial с† 0 the increases 1110 the segment smaller 1055 tensioning prestress due to سه • the prestress But the positive prestress 1055 friction is operation н. Ю loss for н 0 қ 3.8% prestress segment larger moment segment н 0 Н 20. ₩ 64 due 20. segment lost The ő 1 1 1 e due с С net 20 ц О

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} s († 17 <del>(</del>) 17 († increases 8 o 5114455 m bonded than creep ioment **H**-b c ρ bottom fiber h that for result After strain 07785S Strass գ գ 0 beau. 5507 due 4170 с† О takes the prestress ы. М corresponding 60 1--rt O segment As prestress prestress the result also reduced. compared the Стеер place. amount <del>س</del> and shrinkage, and consequently рі († Р. М 1055 to the H L a 0 14 days 11 0 transferred the 0 strain 6 1 1 9 1 1 1 н 0 1 the Þ ц ор slight larger reduction in the after segment prestress fiber increase increase t 5 6 compressive due 20 compressive transfer 1-50 н. СО becomes to the reduced, larger р. Д bending the stress. н 0 1 large prelarger н он strain d o b conthe Ħ

σ († bending Hhe 4 1 1 0 respondingly, ö onded riber 1 unbonded 20 74 When bean, ge r increases 1 1 1 0 0 lnd decre be am prestress loss for segment 1 1 1 1 decreases live load • 17 e segment the compressive . O M change 4176 ۱... those w applied, prestress н. И is uniform H0 H0 H 10t 474 strain affected the loss bottom 20 19 along resulting and н 0 1 р А 5 4 1 1 A S S \*\*\*\*\*\* decreased the each bending upward lower tendon. for the 73 0 11 001-10 J the 1 1 0 1 1

U 001 th n o due ing. ដ +prestress large crease fiber ŏ ţ. 3 H, ID rease b b ased н 0 Е ipanied <del>п</del> the н с† 0 24 and ... 16 17 17 17 17 17 N increase Afterwards, 0 0 11 fiber, oreep in figures \*\*\*\* positive again ٨q t S e t b e ព រា ខ loss. the and the positive bonding during this after prestress loss compressive the increase せたきせ 0 Fh increased due loading bending. shrinkage decrease 17 27 0 стеер 9 C 1 loading. net t 12 e compressive in the 1: D strain increase ր. 0 compressive and the Prestress rt O for segment the This neglible earlier стеер ր. Ծ compressive results 0 M relaxation counteracted strain loss and the compressive since strain period 20 also shrinkage. period frog н 0 н are цре <u>stress</u> т 0 К increases following increases the p poth հ smaller indue the large to n n o u . the decreased 0 1 т 0 т 00 00 strain ∑ ₽ the loadinц. Э – the а С -10 10 11 t De Ð

ሳ and ΰ t b e 0 counts 1035 restress .91. reep unbonded analysis fron » et њ 0 н Thus, years t ne 2055 t he subtracting beams. shows total н 0 11 1055 after 811 1 the 0 loss, creep The the the 8.32. total the initial loss and the **Ave**rage transfer segments 2022 чц and shrinkage loss due 4 7 7 0 0 ₽-. 60 absence 284. prestress 198 0 50 50 54 The 0 relaxation 0 poth 1033 the 11 17 0 concrete relaxation bonded ci u e average 11100 14 14 0 load, 0 0 1

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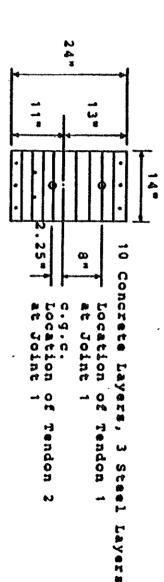
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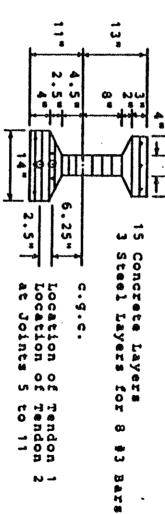
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₽ig. 8.9.2 ÷ Example œ \$ w ŧ α reckenridge-Bugg Beam

(d) C2088 Section 101 Elements ---and 2

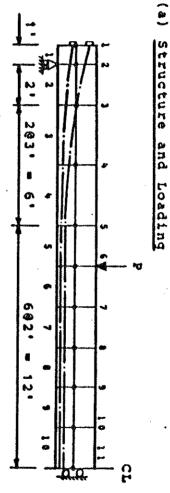








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2 Concrete Properties

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Eq. (8.1) : a1=2.7247, a2=2.6202, Eq. (3.44) for a1's at Loading Ages to r1=0.35, r2=1.865 in Eqs. () Es(T) = T Esu=366×10-6 Esu=258×10-6 м н 0 0 п п (3.39) 2, age1.6390 Later Than To. Bonded 0 = 0 Days 3428

Days

9 Reinforcing Steel Properties (#3 Bars) \*\*\*

Unbonded Bean

- £sy=45 ks1, Esu=0.16, Esu=29000
  Area(1n<sup>2</sup>) and the Distance from
  Asu=0.33, Asu=0.22, Asu=0.33
  ysu=11.3125, ysu=6.25, ysu= c.g.c. kai, 2<sub>82</sub>=100 c.g.c. of 3 S (\* e e 1
- y:3=-9. 3125 (17 inches)
- 0 Prestressing Steel Properties (1.125\*\* Bars)

  - - Layers

72=130 ksi, E2=0.006, 45, 21=24500xe1 €3=0.05

ksi,

E1=0.0045,

the Stress-Strain

Curve

\*\*

Priction Coefficients : fy=130 ksi in Eq. (6.11 Discreta nationed

Eq. (6.13) for

Relaxation

: µ=0.2, ksi)

**X**=2.

5×10

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rad/in

A=0.994 in<sup>2</sup>

572 Ø ٠ Ø U . Example œ \* ÷... 1 Material Properties

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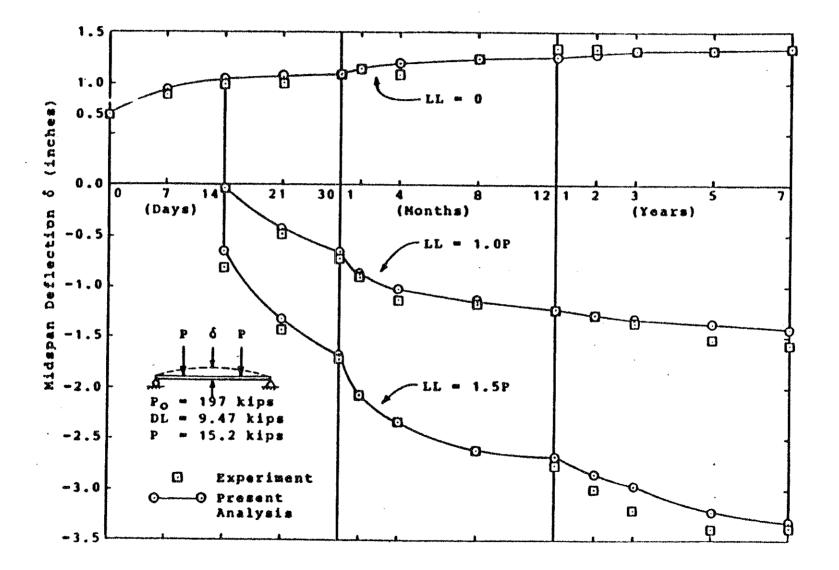
7.201.0 8.9. Example 8 • . • μ 1 Summary of Midspan Deflection

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- . Live load for both unbonded beams is 1.0P. Unbonded beam (2) is analyzed with the same shrinkage data as bonded beams.  $d_1$  and  $d_2$  represent the initial camber and the 7-yea: camber for LL=0. For other cases, they represent the instantineous deflection and the 7-year deflection due to loading, respectively. 7-year the

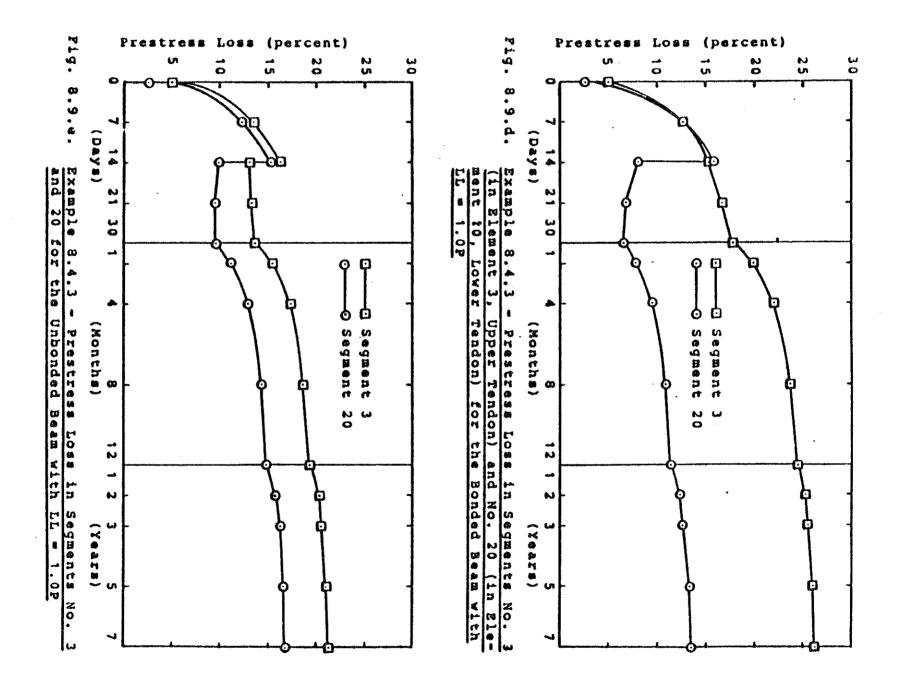
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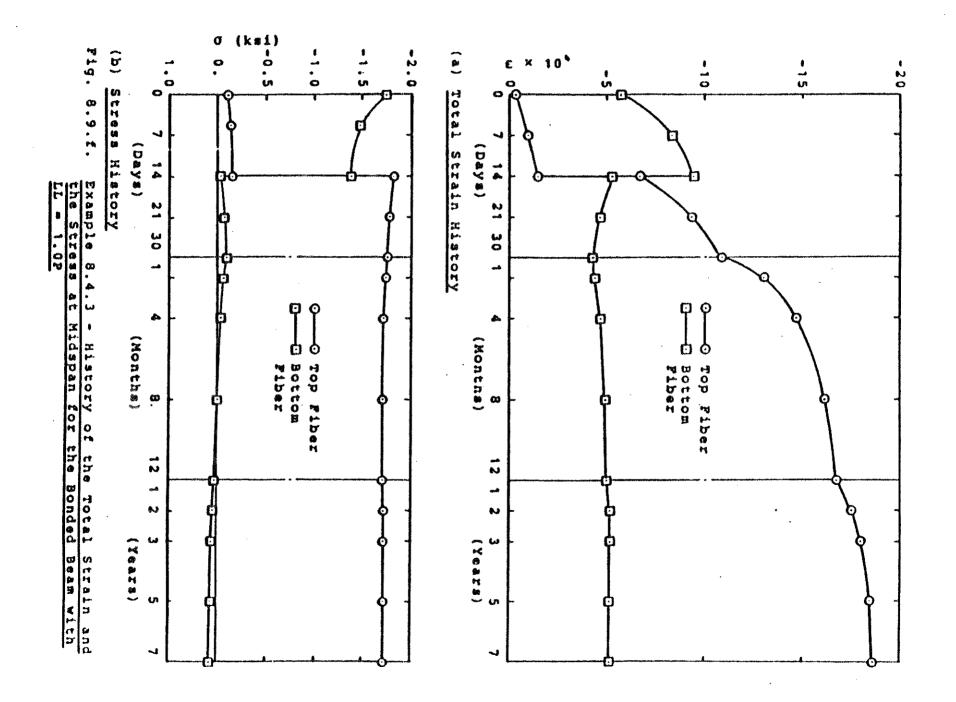
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77.	Exp.		Exp.	<b>Th</b> .	exp.		78	5×	3Y	24	31	80 M	4 3	23	X	21D		 &- D	70	0		-) 
1.91	1.96	ω	1.35	0.70	0.69		1.34	1.33	1.31	1.30	1.26	1.25	1.20	1.15	1.10	1.07		1 0 4	0.94	0.70	11=0	Во
2.30	2.46	•	2.48	1.06	1.01		-1.41	-1.38	-1.34	-1.29	-1.22	-1.15	-1.02	-0.88	-0.65	-0.42	-0.03	1.03	0.94	0.70	LL=1.0P	nded Be
2.58	2.42		4.38	1.69	1.81		-3.33	-3.23	-2.96	-2.86	-2.68	-2.61	-2.33	-2.07	-1.69	-1.32	-0.63	1.03	0.94	0.70	LL=1.5P	₽. 13 \$4
2.30	2.28	<b>a</b> (	2.35	1.07	1.03	-	-1.42	-1.39	-1.34	-1.30	-1.23	-1.17	-1.04	-0.89	-0.67	-0.43	-0.03 .	1.04	0.94	0.70	80 a m	Unbonded
2.31		2.50	1	1.08			-1.46	-1.43	-1.38	-1.34	-1.26	-1.20	-1.06	-0.91	-0.68	-0.44	40.04	1.04	0.94	0.70	(1)Beam (2)	Unbonde dUnbonde d



#### Fig. 8.9.c. Example 8.4.3 - Comparison of Midspan Deflection for Bonded Beams

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ь Aroni Column 1 Geometric and Material Nonlinear

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# Analysis of a Pre-tensioned Column

present designated predict ο pre-tensioned concrete various Ēħ prestress. Aroni conditions geometric nonlinear analysis the strength y V G (63,64) A230c5, т 0 also 0 H tested 0 լ... հյ eccentricity, slenderness presented an analytical procedure columns these analyzed P series columns. л 0 rto trest study their behavior 0 procedure. eccentrically One of the accuracy the columns, and 4 1 9 1 1 Loaded under 0 m amount ő the

1 1 9 е т then where shortening produce the the sumed 4 1 0 0 Drestress.was 572 14171 eccentric load was 4142 loading was initial Force load One cured TOUT 8.10.a. 9 11 <del>0</del> •0 5 H prestress N 1--11815 8 7 8 S 7 8 t ne ت 0 structure 0.198 in. 0 170 under recorded compressive analysis applied н 0 concrete 0 released 176 axial recorded 69 69 computed Sater 11 D 🖷 00 applied up to failure. and ກ ດ 1 diameter <u>i</u>n. Force concrete stress. with the column is analyzed that р th its material properties are specified until \*• in the experiment. 9 t r e s s ď 29 long 14 days 0 0 t ne follows considering 4 high tensile steel wires. 28 days after P/(1 initial prestress which would column was axially concrete 0 prestress was released in the references. 2265 psi for the after EsAs (EcAc) The after casting wi th initial casting, The amount Thus transfer. Ņ the 0 elements. ы. ft pre-tensioned 15600 prestressconcrete shown concrete, when elastic ----10 However when 0 as = lbs, The 0 C 1 1.2 5 14 1770

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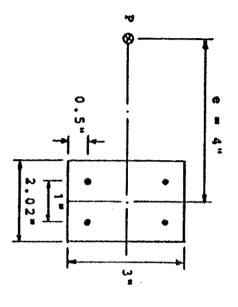
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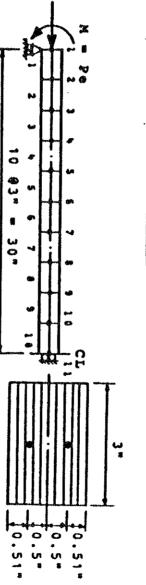
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(6) Finite Mesh Layout

(0) Concrete Properties

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<u>(</u>) eu Prestressing Steel -Properties н +11 558.5 (0.198"¢ 1 8 C

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Ptg. 8.10.5. Deflections Example <u>.</u> ھ ٠ \$ 1 Comparison °, Midspan

Midspan Deflection & (inches)

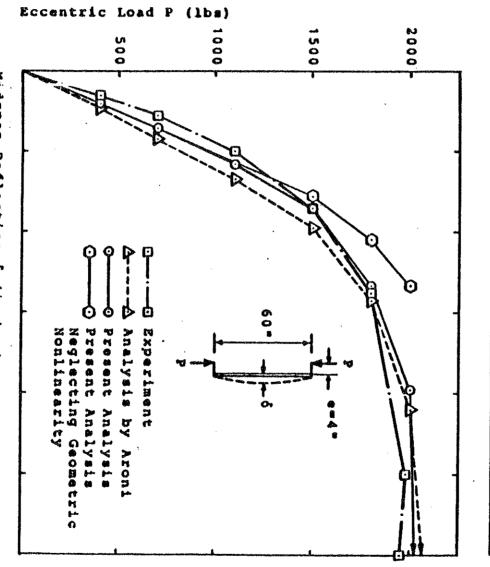


Table 216361C 8.10. anal: yais Example neglecting ω • a \* ŧ geometric Midspan Deflections nonlinearity

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2000	1800	1500	1100	700	400	ې (152)
	0.55	0.34	0.20	0.11	0.06	5x2.
0.84	0.57	0.39	0.27	0.17	0.09	Aroni'a Analysis
0.79	0.53	0.34	0.23	0.14	0.08	Present Analysia
0.53	0.42	0.31	0.22	0.14	0.08	Aroni's Present°Present AnalysisAnalysisAnalysis

α 1

14.3 ¥ 1 ¥ ы 19 0 0 0 5 divided 0 H (0 5 1-1divided modeled into into by two concrete 10 prestressing segments. layers. The steel prestressing tendons each steel 0

У Ч 2000 9 H 1 C a n г† р/ }~ ana <del>ц</del>р6 results agreement With tabulated ty considering Ē and analytical 055000 0 yzed the lbs. H 0 H load observed. 10 10 にはため displacement between 1 1 17 9 7 1 0 111 The both steps table 9 11 1 9 1 column ក ភ្លា ព t 17 @ average the present analysis and Aroni's t 7 e 0 7 0 geometric The material material results 8.10 Can experimental result significance ratio used number and 0 0 11 0 nonlinearity only. for the plotted nonlinearity tolerance nonlinearity noted 0 11 analyze iterations froa 0 midspan deflection in Fig. 0 Hi the the the result the only. 0.01 is and the analytical geometric column ден 8.10.5. uuntoo H L e load 4 с Р analysis obtained experimenր. ն nonline**n**t Ø н 0 0 Good are d e 1 91.00 ъ study ۵

000 4176 œ rt L described duced during table . 9 S 6400 periphiral time H n e Summary f t o a 8.11 9 11 9 12 computer examples in chapter summer the FORTRAN along with 0 processor the 0 Hij с 17 presented Computer 4 1976. the University the xora source programs 5 H H H H parameters which used. 5 In most Time and th1 5 and t n e The Cases, of California, chapter 0051 Cost central **RCT RAME** 10 17 0 r 0 affect load modules vere the processor and tabulated run the Berkeley PCFRAME Examples 0 soluthe 0101 tiae, ч. Э

joints, Among elements 4170 parameters and layers listed dictate 5 the the stor table, 9 â ø the 2 1 R numb 0 and t D e 0 fh

equations. formation of total 0050 erage ¥ 4 5 For the กนสปัด r central processor \$4.5. 0 Hi the -0 examples iterations stiffness and . time was . presented . dictates the time the solution of equilibrium 30 seconds ĺn this chapter, and the required average t n e **Н**О-1 avt n e

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Example	MN	GN	NJ	NE	NCL	NSL	NPS	NTS	NLS	NIT	CP(#ec)	PP(sec)	COST(\$)
8.2.1	NO	YES	6	5	10	0	0	1	12	3.3	6.5	6.1	1.5
8.2.2	YES	YES	11	10	14	1	0	1	10	5.0	21.7	8.5	1.9
8.2.3	YES	NO	7	6	10	2	0	1	20	.11.5	45.2	7.7	5.6
8.3.1	YES	NO	17	16	19	4	0	1	10	5.5	59.6	25.6	10.2
8.3.2	YES	NO	16	15	15	.3	0	20	20	2.7	76.4	27.4	8.6
8.3.3	YES	NO	2	1	10	1	0	17	17	2.2	4.6	12.6	1.6
8.4.1	YES	NO	11	10	10	1	10	2	10	4.8	22.0	9.6	2.6
8.4.2	YES	Ю	11	10	14	0	10	10	10	3.4	26.0	9.7	4.3
8.4.3	YES	NO	11	10	15	3.	20	13	14	2.9	38.3	24.2	6.7
8.4.4	YES	YES	11	10	10	0	20	2	7	3.9	20.1	10.6	2.2

- (1) MN : Material Nonlinearity
- (2) GN : Geometric Nonlinearity
- (3) NJ : Number of Joints
- (4) NE : Number of Elements
- (5) NCL: Number of Concrete Layers
  - (6) MSL: Number of Reinforcing Steel Layers
- (7) NPS: Number of Prestressing Steel Segments
- (8) NTS: Number of Time Steps
- (9) NLS: Total Number of Load Step
- (10) NIT: Number of Iterations per Load Step
- (11) CP : Central Processor Time
- (12) PP : Peripheral Processor Time

Table 8.11. Summary of the Computer Time and Cost for the Examples

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9 CONCLUSIONS

Q Summary

ø throughout their and internal ented. due S C T T S geometric lastic, ß aging rt 0 ssed concrete An efficient load history, The method is capable inelastic forces, 0 H nonlinear concrete, service load history stresses and frames including the numerical and ultimate analysis temperature history, creep, shrinkage relaxation procedure of planar 0 h strains load predicting of prestress has been presranges. as well as throughout 0 M H O H time reinforced and these structures the dependent the material displacements, -eid 01100 and rተ ຜ

9 1 1 1 9 tions. 0 tilized properties tions which Total, finite nonlinear into ward virtual unbalanced load iterations for each load ₿ŧ integration FOT element method based on the displacement incremental and tangential form of equilibrium equah or discrete the equilibrium equations work. at any instant the solution are quasi-static time valid for number is performed by dividing the time An incremental load method combined with 0 H 0 m 0 14 the intervals. t i Be current geometry and material dependent analysis nonlinear are set up and solved by the are . • derived For each time equilibrium equaincrement is by the principle formulation. ¢۵ domain interval step forц Т

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Шa are steel, ω rt n H βυ ທ R ion F ø Б d hrinkage rt terials H lationship. .ve ω uti incorporated in the א. רו . ц. Д 0 Њ respectively. lized Bilinear the μ. S concrete 6 ő the aging independent for account inst The and multilinea and temperature the բ. Տ antaneous non-mechanical Hi O H approximated reinforcing Simple variable stress-strain curves the stra load unloading and н forms ц Ц <u>г</u>. Б variation. steel А 0 reversal. strain due the a parabolic-linear 0 Hi and t 0 nonlinear stresst 5 1 1 1 shortreloading the due н 0 1 Stress-strain ט א in it ů, t 1 me the STRESS -ወ (A rain curves 010 rt H three models ø Ч о n ñ ρ Ω Ŵ Ω, funct ş.... strain э ... g р Q ų.

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يب. ون displacement ø ρ length. 0 t prestress. unbonded frames rt, F. lement 5 'n developed n span rete analysis Hbr properties an element 0 0 The number distinct Prestressing steel incompatibility. н 0 5 0 H contribution of о њ \*\*\* pre-tensioned the unbonded 1.e. are added and linear stages have before; segments 0 14 ρ directly. the structures to constant and loading tendons at and after prestressing post-tensioned each are 9 T 0 stress An of which is distinguished divided iterative account the transfer along steel bonded into HOH i ts nt O assumed method the t T D d <u>م</u> and ц. Ц 0

ы 0 H H validity O. esults omputer compared Finally, and programs developed are presented to with applicability ۹Q series of numerical examples experimental 0 the data present and other method. investigate analyzed theoretical The results А Д the the

#### 9.2 Conclusions

m 5 concrete rt 0 airly ād predict including the load . accurately. frames The the present response subjected numerical procedure due 0 Hi 0 11 planar to environmental 410q short-time reinforced has variation and and been prestressed longdemonstrated -t+ne

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cluding ω • t n e The efficient present time numerical dependent formulation analysis 0 F procedure creep predic 1 1 th,

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APPENDIX

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#### RCFRAME Input Instructions

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### PCFRAME Input Instructions

The fol fol ollowing program inf RCF ormation 'RAME (U Ω H ø μ. -nput н р addition († Ö tho Ŵ ወ

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N 4 21 u ----------٠ ----σ σ **....** Т ŧ ω 1 I ł . ů. 4 ω O N \_\_\_\_ υ. o õ  $\mathbf{O}$ S UN. 0 10 ard, skip if (AGEPS) Coeffici (CRPS) I (FPSY) Time in KBOND=1 KBOND=0 U O ħ 0.18 (NPT, operation until constant force (NPS
No. of points used is. Prest: KPS=0 and has No. KPS# length ond oefficient CRPS) Enter restressing straight, spans a prestressing 0 Fh 0 Ħ ρ μ <u>ه</u>ب 000 offset max. constant given profile, initial tensioning force ۲. ы. Н prestressing prestressing steel թեր Իդեղ days (NTND, Ø post-tensioned pre-tensioned (KBOND) bonded unbonded н S i Frame KPS=0 ŀή yield ÷ 0 <del>.</del> elapsed type пах. H cross-rectional . н тре rt steel ransfer stress rt 0 code Ĥ 1----÷ ŝ O. 3 calculation ordinary J steel from 1th Bax. conc ormation excluding specify (KP н 0 Ч 0 rete 60) initial m segments rt ŵ endons pre ъ ס, Ħ stress-strain menb 0 1  $\overline{}$ H S area 0 N ወ rt rt н () -Hh rt 50 ressing | თ rt. ensioned tensioning ō each relaxat. ressing each H. N origin along m and 10 ing 0 of which • 1h 2 has S whi i o n rt իս Մ steels n Ø ase Ł ø CUIVE in, F ω 0 10 0 57 ដុ S ÷ Ø

F 1 1 ωΝ ----00  $\mathbf{O}$ Wobble Curvatu Symmetry KSYN#1 KSYM=0 цц if the structure or if the structure and friction coefficient ure friction coefficient code (KSYM) oeffici and . @ ] اسور loading K (CXPS) oading ŕt Ц (CMUPS) μ. ß ທ 5 ц 0 syn ct symme ii o ct H rt н. 0 13 ці. О

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ω 0 1 1 σ **υ** ω  $\sim$ -+ ~ 10 -6-25 دت ا ጥ . ----መ σ σ ì ი ... 1 I ٠ 1 ŧ N ديا 1 Ï. 1 ъ 4 ω υ υ ວ່ທ **.....**8 . 80 . 4 ω N <u>\_\_</u> • σ <sub>υ</sub> ວທ ហ տտ 010 I M 110 are ЬŇ re Joint Joint No. Pres No. segm Area Forit the the the ы ເກ (P (ECCI(I)) 0 0 0 n, C a ഗഗ U H 0 000 0.0 H H H H H H in I êg egne ភ្នំ ወ end stressi for ress [rt gme in O igin entric <del>کر ار</del> He H B horage sl dded 0 ħ total symm ο rt . symme μ. æ o o tens positive Hh. H lu, о ц н н ard ы 5 Ħ B Ð N | G H essing th rt et. rt rt prestressing concre d (MPS 6 0 0 ing - tendon
- tensioning
metric postsionir
sionir (PS and FOM μ. z . нод 5 но 6 « ing S: рц Ø **j\_**\_\_ 0 22 0 н. 11 t K +h 0 . 5 7 4 S . re in ] ?(I), P: а<del>т</del>т отта Ý S (N S I Ծ Stee c† ~ prestressin ц. b rt. õ 0 H н train 0 5 1 n (I) - rt β¢ rt S ۱o rt Ð . Ťh ው upward ct e 10 ъ • member ach ioning 0 Hi νō 1 **t** 1 e 1 rt ct (NTPS(I)) the joj. oper ends Пe 0 point No.
SE(I);I=1, st-tens Ø :5 Ы 5 Ø Leave ndon (NLAST n (ATND(I)) g force of 1 t-tensioned Tendon rope ä egment the то та т values Â, ά 1as segment aber in 0 H H 105 prestress ល t j (ECCJ(I))
f the prestressi
(THPS(I)) from force H st (v MPS(I) rt H S († ú. 5 4 e nd ioned rt H ioned lank μ. pres щ n н Stee C† ο n ד בי ט מ , order , NPT) w member ¥Ъ ad st outs a H N ίΩ H ٥, tendon 4 N O ST(I)) i ng Ю ۳, orma stres eac 6 (I) (I) t t t e a 1. 1 ing (SLI for n . μ **'**U' a se F D (315, 0 I 6 5 ET. H D N ~ ft segment LIP(I)) Ø £† member rt. excludi ω end 1h n rt ١0 Ø μ. point 6 :end reference stee 9 2 1. pre-tens ente o ي المراج p.... S 0,7 n ne d s i n n 9 et D b μ. 3E10. p Ω. b Ó whi i) rt 10 0 ŝ 5 ÷. Ð 1 ste ω gme H 14 n b---c half or assumed n n n n coordinates ò -v segment 0 symme rt **U**1 (PZERC(I)) half of 9 :3' C Ħ ŵ n <u>н</u>. О Ħ ۵, Ø 4 ወ w 4170 († 11 0 فسؤ ş...... P11 axi 0 H H 0 1 Ô Э m rt H ş.e. D⊫ H n 0 one Ø ä o . n n പ് Ηţ իս 1 9 ρ ct ហ I

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