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## Physical Damage-Measured Response Correlation for Nonstructural Components Tested under Multi-hazard (Earthquake and Fire) Demands in the CFS10 Building

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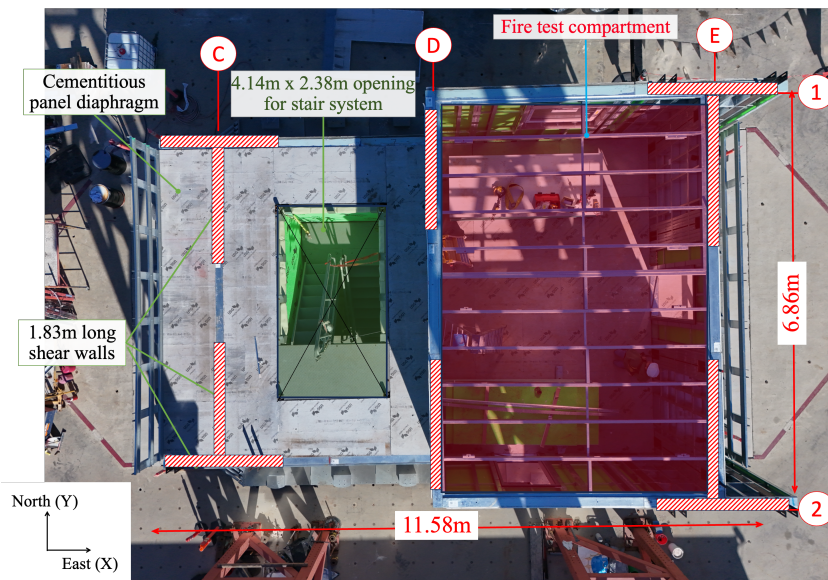
### ABSTRACT

This paper is the second of a set presented within the session: *Findings from the CFS10 Multi-Hazard Test Program*. The emphasis within this article is to highlight correlations between physical damage to nonstructural components and systems with measured response during a suite

of 18 earthquake tests and two subsequent fire tests. This damage was documented within a 10-story cold-formed steel-framed building test specimen outfitted with various nonstructural components, including suspended ceilings, architectural finishes, a resilient stair system, windows and doors, pressurized fire sprinkler and gas piping systems, and roof-mounted mechanical equipment. The test building and multi-hazard protocol are described in the session companion paper. This paper provides test observations correlated with measured engineering demand parameters such as floor acceleration, building inter-story drift or peak local temperature responses and offers related literature emerging from the project. Damage data and functionality checks will support development of fragility functions for these nonstructural systems for use in recovery-based frameworks.

## INTRODUCTION TO CFS10 PROGRAM

A 10-story cold-formed steel (CFS) building, referred to as CFS10, was tested at the 6-DOF Large High Performance Outdoor Shake Table (LHPOST6), part of the Natural Hazards Engineering Research Infrastructure at University of California San Diego (NHERI@UC San Diego; McCartney et al., 2025). The test building had plan dimensions of 11.58 m (X-direction, east-west) by 6.86 m (Y-direction, north-south) and a total building height of 31.6 m (to the top of parapet), see Figure 1. Interested readers are referred to Hutchinson et al. (2026a, 2026b) for an overview of the experimental program and Singh et al. (2022, 2024) for details about the structural design.



**Figure 1. Annotated photograph of the CFS10 building floor plan.**

### *Seismic and Fire Test Protocols*

The test specimen was subjected to increasing intensity multi-directional seismic excitations and subsequently to two compartment fire tests. 18 earthquake motions (MID1-MID18) were imposed on the specimen, including 15 service-level earthquakes (SLE), one design earthquake (DE), and two risk-targeted maximum considered earthquakes ( $MCE_R$ ). Following the seismic tests, Levels 6 and 9 of the building were subjected to fire tests for post-earthquake fire performance evaluation. Seismic and fire test matrices are provided in the companion paper (Hutchinson et al., 2026b).

## SCOPE OF THIS PAPER

### *Nonstructural Components and Systems (NCSs) in CFS10 Building*

The CFS10 test building was outfitted with a wide range of NCSs including fire sprinkler and gas piping systems, suspended ceilings (Singh et al., 2026), a resilient stair system (Sorosh et al., 2025), windows, swing and roll-up doors, roof-mounted mechanical equipment (Zhang et al., 2026a, 2026b), architectural wall and ceiling finishes, and firestop and protection materials. These systems, shown in Figure 2, were distributed across the different levels of the building. The NCSs as presented in this paper are organized following Sections 13.5 and 13.6 of ASCE 7-22 (2022) in Tables 1 and 2 providing a detailed description of the various components. Recent publications emerging from the project have discussed the seismic response of select NCSs. This paper provides physical test observations correlated with measured engineering demand parameters (EDP) such as floor acceleration, building inter-story drift or peak local temperature responses for NCSs.



**Figure 2. Nonstructural components and systems installed in the CFS10 building.**

### *Nonstructural Element Database (NED)*

The U.S. National Institute of Standards and Technology (NIST) has developed the Nonstructural Element Database (NED) to address this critical data collection and dissemination gap (Cook et al., 2026). Effort at NIST has focused on consolidating data from the past two decades of experimental studies into an open-source public repository. Including the data from the pre-2010 studies, cited in the FEMA P-58 (FEMA, 2012) background documentation, it currently contains over 2000 test records. Figure 3 shows the data schema of NED (Cook, 2025). The formatting of datapoints reported in this paper follows a similar schema used in NED, using UNIFORMAT II element classification system (Charette and Marshall, 1999) to categorize building components. Based on attributes of detail, material and size class, the components are further subcategorized,



providing further structured detail in Tables 1 and 2. In the following section, the physical observations for each component in an inspection sequence are provided, noting if any repair actions were taken and assigned one of the following damage classes: (a) no damage, (b) inconsequential damage, i.e. primarily aesthetical, or (c) consequential damage i.e. impacts operation/functionality and may require repair actions.

| Experiment              |                                  |                                     |                     |
|-------------------------|----------------------------------|-------------------------------------|---------------------|
| <b>id</b>               | <b>CharField</b>                 | <b>edp_value</b>                    | <b>DecimalField</b> |
| <b>component</b>        | <b>ForeignKey (component_id)</b> | <b>governing_design_standard</b>    | <b>CharField</b>    |
| <b>reference</b>        | <b>ForeignKey (id)</b>           | <b>loading_protocol</b>             | <b>TextField</b>    |
| <b>alt_edp_metric</b>   | <b>CharField</b>                 | <b>location</b>                     | <b>CharField</b>    |
| <b>alt_edp_unit</b>     | <b>CharField</b>                 | <b>material</b>                     | <b>CharField</b>    |
| <b>alt_edp_value</b>    | <b>DecimalField</b>              | <b>notes</b>                        | <b>TextField</b>    |
| <b>comp_description</b> | <b>TextField</b>                 | <b>peak_test_amplitude</b>          | <b>CharField</b>    |
| <b>comp_detail</b>      | <b>CharField</b>                 | <b>prior_damage</b>                 | <b>TextField</b>    |
| <b>design_objective</b> | <b>TextField</b>                 | <b>prior_damage_repaired</b>        | <b>TextField</b>    |
| <b>ds_class</b>         | <b>CharField</b>                 | <b>reviewer</b>                     | <b>CharField</b>    |
| <b>ds_description</b>   | <b>TextField</b>                 | <b>size_class</b>                   | <b>CharField</b>    |
| <b>ds_rank</b>          | <b>IntegerField</b>              | <b>specimen</b>                     | <b>CharField</b>    |
| <b>edp_metric</b>       | <b>CharField</b>                 | <b>specimen_inspection_sequence</b> | <b>CharField</b>    |
| <b>edp_unit</b>         | <b>CharField</b>                 | <b>test_type</b>                    | <b>CharField</b>    |

**Figure 3. Nonstructural Element Database (NED) data schema (Cook, 2025)**

**Table 1: Description of NCSs (ASCE 7-22, Section 13.5) installed in CFS10 building.**

| Component                                                                                                                                                                                                                                                                                                | Fragility classification number | Governing design standard  | Location                         | Detail                                     | Material                                        | Size                                             | ID |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|----------------------------|----------------------------------|--------------------------------------------|-------------------------------------------------|--------------------------------------------------|----|
| Ceilings                                                                                                                                                                                                                                                                                                 | C303                            | ASCE 7-22, ASTM C1858-24   | L10 west room                    | Suspended – fixed-fixed                    | Lightweight gypsum board (9 kg/m <sup>2</sup> ) | 13.4 m <sup>2</sup> < Area < 92.9 m <sup>2</sup> | C1 |
|                                                                                                                                                                                                                                                                                                          |                                 |                            | L10 east room                    | Suspended – floating-fixed                 |                                                 |                                                  | C2 |
|                                                                                                                                                                                                                                                                                                          |                                 |                            | L1-9; L10 balconies              | Direct attachment                          |                                                 | –                                                | C3 |
| C1: 4.41 m by 6.55 m suspended ceiling system, seismically unbraced, all edges fixed. Main tees spaced at 1.22 m; cross tees spaced at 0.41 m; hanger wires spaced at 1.22 m. 16 mm thick gypsum board attached using #6 screws at 0.3 m spacing. 1.22 m by 1.22 m opening for ships ladder.             |                                 |                            |                                  |                                            |                                                 |                                                  |    |
| C2: 4.41 m by 6.55 m suspended ceiling system, seismically braced using splay wires and compression posts, two floating and two fixed edges. Main tees spaced at 1.22 m; cross tees spaced at 0.41 m; hanger wires spaced at 1.22 m. 16 mm thick gypsum board attached using #6 screws at 0.3 m spacing. |                                 |                            |                                  |                                            |                                                 |                                                  |    |
| C3: 16 mm thick gypsum board attached to resilient channel using #8 screws at 0.3 m spacing.                                                                                                                                                                                                             |                                 |                            |                                  |                                            |                                                 |                                                  |    |
| Interior wall finishes                                                                                                                                                                                                                                                                                   | C301                            | AISI S100-16, AISI S400-20 | All levels                       | Direct attachment                          | Gypsum board                                    | –                                                | W1 |
| W1: 16 mm thick gypsum board attached directly to CFS framing using #8 screws at 0.15 m/0.41 m (perimeter/field) spacing.                                                                                                                                                                                |                                 |                            |                                  |                                            |                                                 |                                                  |    |
| Exterior wall finishes                                                                                                                                                                                                                                                                                   | B201                            | AISI S100-16, AISI S400-20 | All levels: exterior face Line 1 | Direct attachment                          | Gypsum board, stucco                            | –                                                | W2 |
| W2: 16 mm thick gypsum board attached to CFS framing using #8 screws at 0.2 m (perimeter and field) spacing. Exterior Insulation Finishing System (EIFS) installed over the substrate panel.                                                                                                             |                                 |                            |                                  |                                            |                                                 |                                                  |    |
| Stairs                                                                                                                                                                                                                                                                                                   | C201                            | ASCE 7-22                  | L1-9                             | Scissor stairs – drift release connections | Steel                                           | Plan: 4.14 m by 2.38 m                           | S1 |

S1: Prefabricated scissor-configured steel stairs with various drift-release connections, including (1) drift-compatible connections featuring a continuous attachment channel (L1, L6), (2) drift-compatible connections featuring split attachment channels (L2, L4), (3) modified drift-compatible connections (torsion bar) featuring a continuous attachment channel (L3, L7), and (4) sliding (free) connections (L5, L8, L9).

|                                                                                                                                                                                                                                                                                                                                 |      |                                                |                   |                                   |                    |                                 |    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|------------------------------------------------|-------------------|-----------------------------------|--------------------|---------------------------------|----|
| Interior doors                                                                                                                                                                                                                                                                                                                  | C102 | ANSI/SDI<br>A250.8-23/<br>NAAMM<br>HMMA 810-09 | Various locations | Swing – fire-rated                | Metal              | 1.02 m by 2.18 m                | X1 |
| X1: Line C (open): L2; Line D (closed): L2, L3, L6, L9; Line E (closed): L3, L6. Hollow-metal swing doors with cylindrical door latch. 90 min fire rating for door, 20 min fire rating for door frame.                                                                                                                          |      |                                                |                   |                                   |                    |                                 |    |
| Exterior doors                                                                                                                                                                                                                                                                                                                  | B203 | NFPA 80                                        | L2 stair landing  | Roll-up – fire-rated              | Metal              | 2.15 m by 2.79 m                | X2 |
| X2: Galvanized steel roll-up door. Chain hoist operated. 90 min fire rating. Guide frame and square hood attached to columns and channel band of modular stair system.                                                                                                                                                          |      |                                                |                   |                                   |                    |                                 |    |
| Exterior windows                                                                                                                                                                                                                                                                                                                | B202 | AAMA/<br>WDMA/ CSA<br>101/ I.S.2/<br>A440-22   | L1-2, L6          | Dry-glazed stick built, resilient | Tempered           | Insulated glazing units (IGUs). | X3 |
|                                                                                                                                                                                                                                                                                                                                 |      |                                                | L3, L10           |                                   | Laminated          |                                 | X4 |
|                                                                                                                                                                                                                                                                                                                                 |      |                                                | L4-5, L8          |                                   | Heat strengthened  |                                 | X5 |
|                                                                                                                                                                                                                                                                                                                                 |      |                                                | L1, L3, L6        | Dry-glazed stick built            | Tempered           | 1.42 m by 1.22 m                | X6 |
|                                                                                                                                                                                                                                                                                                                                 |      |                                                | L4, L8, L10       |                                   | Laminated          |                                 | X7 |
|                                                                                                                                                                                                                                                                                                                                 |      |                                                | L2, L5            |                                   | Laminated-annealed |                                 | X8 |
| X3-X5: West room Line 1. Aluminum-framed, double pane, fixed windows. Sliding detail to accommodate drift. X6-X8: East room Line 1. Vinyl-framed windows. L1-4: triple pane; L5-6, L8, L10: double pane. L1, L3-4, L6, L10: operable; L2, L5, L8: fixed. 16 mm clearance between glazing and window frame to accommodate drift. |      |                                                |                   |                                   |                    |                                 |    |

**Table 2: Description of NCSs (ASCE 7-22, Section 13.6) installed in CFS10 building.**

| Component                                                                                                         | Fragility classification number | Governing design standard | Location                 | Detail                                     | Material | Size                                | ID |
|-------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------|--------------------------|--------------------------------------------|----------|-------------------------------------|----|
| Fire protection system – sprinklers                                                                               | D401                            | ASCE 7-22, NFPA 13        | L2-3, L6, L9             | Braced pipes, standard drop – no ceiling   | Steel    | ϕ73 mm main and ϕ48 mm branch lines | F1 |
|                                                                                                                   |                                 |                           | L10                      | Braced pipes, standard drop – soft ceiling |          |                                     | F2 |
|                                                                                                                   |                                 |                           |                          | Braced pipes, flexible drop – soft ceiling |          |                                     | F3 |
| F1: Main and branch line pipe seismic bracing against floor joists with standard rigid drop through no ceiling.   |                                 |                           |                          |                                            |          |                                     |    |
| F2: Main and branch line pipe seismic bracing against floor joists with standard rigid drop through gypsum board. |                                 |                           |                          |                                            |          |                                     |    |
| F3: Main and branch line pipe seismic bracing against floor joists with flexible drop through gypsum board.       |                                 |                           |                          |                                            |          |                                     |    |
| Fire protection system – standpipe                                                                                | D402                            | ASCE 7-22, NFPA 13        | L1-9                     | Braced riser pipe                          | Steel    | ϕ114 mm                             | F4 |
| F4: Riser pipe going through stair mid landing and four-way braced against stair channel band every 9.1 m.        |                                 |                           |                          |                                            |          |                                     |    |
| Other fire protection systems                                                                                     | D409                            | ASTM E814-24              | Line D: L3, L9           | Fire sleeve for cable pathway              | Steel    | –                                   | F5 |
|                                                                                                                   |                                 | ASTM D3575-20             | West room Line C: L2, L6 | Bottom track seal                          | Foam     | –                                   | F6 |

F5: Fire-rated sleeve as a cable pathway through walls, surrounding frame to cover any gaps in gypsum.  
F6: Preformed 16 mm thick firestop seal for bottom of the wall joints between bottom track and drywall to floor finish (structural cement panel).

|                                                                                                          |      |                       |         |                                                                  |                   |                                                      |    |
|----------------------------------------------------------------------------------------------------------|------|-----------------------|---------|------------------------------------------------------------------|-------------------|------------------------------------------------------|----|
| Gas piping system                                                                                        | D209 | ASCE 7-22, ASME B31.9 | L5, L10 | Braced pipes – rigid (jointed)                                   | Metal             | ϕ51 mm                                               | G1 |
|                                                                                                          |      |                       |         | Braced pipes – flexible (seamless)                               | Corrugated metal  | ϕ67 mm                                               | G2 |
| G1: Rigid copper main and isolated gas pipe seismically braced against floor joists.                     |      |                       |         |                                                                  |                   |                                                      |    |
| G2: Jacketed corrugated copper alloy main and isolated gas pipe seismically braced against floor joists. |      |                       |         |                                                                  |                   |                                                      |    |
| Roof-mounted mechanical equipment                                                                        | D303 | ASCE 7-22             | L11     | Unit with hard anchorage                                         | Direct attachment | Lightweight slender unit. Maximum aspect ratio = 3.7 | M1 |
|                                                                                                          |      |                       |         | Vibration isolated without seismic restraint                     | Neoprene pads     |                                                      | M2 |
|                                                                                                          |      |                       |         | Vibration isolated with seismic restraint                        | Spring isolators  |                                                      | M3 |
|                                                                                                          |      |                       |         | Unit with hard anchorage                                         | Direct attachment | Lightweight squat unit. Aspect ratio = 1.1           | M4 |
|                                                                                                          |      |                       |         | Vibration isolated without seismic restraint                     | Neoprene pads     |                                                      | M5 |
|                                                                                                          |      |                       |         | M1-M3: Slender air-conditioning condenser units weighing 1434 N. |                   |                                                      |    |
| M4-M5: Squat air-conditioning condenser units weighing 1339 N.                                           |      |                       |         |                                                                  |                   |                                                      |    |

## OBSERVATIONS CORRELATED WITH ENGINEERING DEMAND PARAMETERS

Test observations for the NCSs listed in Tables 1 and 2 are presented in this section. These observations are correlated with a measured EDP in Tables 3 and 4 for seismic tests, and Table 5 for fire tests. For seismic tests, peak floor acceleration (PFA) or peak inter-story drift ratio (PIDR) is chosen as the EDP; while for fire tests, peak temperature measured nearest to component is selected as the EDP for correlation with test observations for the NCSs. It should be noted at this point, that between the seismic and fire tests, the window unit from Level 6 east room (NCS ID: X6) was removed and the swing door on Level 9 Line E (NCS ID: X1) was installed. These configuration changes were necessary to achieve the same ventilation and opening factor for the two fire test compartments.

**Table 3: Observations for NCSs (ASCE 7-22, Section 13.5) from seismic tests.**

| NCS ID                                                                                                                                                                                    | MID | Damage description | Prior damage | EDP                                                 | Damage class |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|--------------------|--------------|-----------------------------------------------------|--------------|
| C1                                                                                                                                                                                        | 17  | C1.01              | –            | $PFA_x = 1.44g$ , $PFA_y = 1.02g$ , $PFA_z = 0.31g$ | –            |
|                                                                                                                                                                                           | 18  | C1.02              | –            | $PFA_x = 1.70g$ , $PFA_y = 0.74g$ , $PFA_z = 0.39g$ | I            |
| C1.01: No damage.                                                                                                                                                                         |     |                    |              |                                                     |              |
| C1.02: No major damage. Instances of minor tilting of screws at individual gypsum ceiling board edges. Minor board crushing at the wall-ceiling interface due to small relative movement. |     |                    |              |                                                     |              |
| C2                                                                                                                                                                                        | 17  | C2.01              | –            | $PFA_x = 1.40g$ , $PFA_y = 1.19g$ , $PFA_z = 0.26g$ | –            |
|                                                                                                                                                                                           | 18  | C2.02              | –            | $PFA_x = 1.67g$ , $PFA_y = 0.91g$ , $PFA_z = 0.40g$ | I            |
| C2.01: No damage.                                                                                                                                                                         |     |                    |              |                                                     |              |
| C2.02: No major damage. Instances of minor tilting of screws at individual gypsum ceiling board edges. Minor board crushing at the wall-ceiling interface due to small relative movement. |     |                    |              |                                                     |              |

|    |    |       |   |                                                                              |   |
|----|----|-------|---|------------------------------------------------------------------------------|---|
| C3 | 17 | C3.01 | – | PFA <sub>x</sub> = 0.87g, PFA <sub>y</sub> = 0.77g, PFA <sub>z</sub> = 0.16g | – |
|    | 18 | C3.02 | – | PFA <sub>x</sub> = 1.18g, PFA <sub>y</sub> = 0.60g, PFA <sub>z</sub> = 0.24g | I |

C3.01: No damage.

C3.02: No major damage. Instances of minor tilting of screws at individual gypsum ceiling board edges. Minor board crushing at the wall-ceiling interface. Tearing, tape buckling and delamination at mud and tape locations (L2 west, L3, L6, L9 east rooms).

|    |    |       |                     |                                                      |   |
|----|----|-------|---------------------|------------------------------------------------------|---|
| W1 | 17 | W1.02 | W1.01, not repaired | PIDR <sub>x</sub> = 0.69%, PIDR <sub>y</sub> = 0.66% | I |
|    | 18 | W1.03 | W1.02, not repaired | PIDR <sub>x</sub> = 0.91%, PIDR <sub>y</sub> = 0.56% | I |
|    | 17 | W1.12 | W1.11, not repaired | PIDR <sub>x</sub> = 0.69%, PIDR <sub>y</sub> = 0.66% | I |
|    | 18 | W1.13 | W1.12, not repaired | PIDR <sub>x</sub> = 0.91%, PIDR <sub>y</sub> = 0.56% | I |

W1.01: Minor damage. Instances of minor tilting of screws at individual gypsum wall board edges. Minor gypsum crushing at wall corners and board-to-board panels interfaces.

W1.02: Permanent offset between gypsum panels. Accumulated fasteners tilting and rotation.

W1.03: Enlarged permanent offset between gypsum panels. Significant number of fasteners show tilt and rotation. Tearing, tape buckling and delamination at mud and tape locations (L2 west, L3, L6, L9 east rooms).

W1.11: Minor damage. Instances of minor tilting of screws at individual gypsum wall board edges.

W1.12: Accumulated fasteners tilting and rotation.

W1.13: Extensive fastener tilting and rotating around door openings and wall panel edges. Gypsum board crushing at bottom tracks.

|    |    |       |   |                                                      |   |
|----|----|-------|---|------------------------------------------------------|---|
| W2 | 17 | W2.01 | – | PIDR <sub>x</sub> = 0.51%, PIDR <sub>y</sub> = 0.41% | – |
|    | 18 | W2.02 | – | PIDR <sub>x</sub> = 0.51%, PIDR <sub>y</sub> = 0.50% | I |
|    | 17 | W2.11 | – | PIDR <sub>x</sub> = 0.59%, PIDR <sub>y</sub> = 0.66% | – |
|    | 18 | W2.12 | – | PIDR <sub>x</sub> = 0.58%, PIDR <sub>y</sub> = 0.56% | I |
|    | 17 | W2.21 | – | PIDR <sub>x</sub> = 0.69%, PIDR <sub>y</sub> = 0.44% | – |
|    | 18 | W2.22 | – | PIDR <sub>x</sub> = 0.67%, PIDR <sub>y</sub> = 0.49% | I |
|    | 17 | W2.31 | – | PIDR <sub>x</sub> = 0.67%, PIDR <sub>y</sub> = 0.36% | – |
|    | 18 | W2.32 | – | PIDR <sub>x</sub> = 0.69%, PIDR <sub>y</sub> = 0.44% | I |
|    | 17 | W2.41 | – | PIDR <sub>x</sub> = 0.63%, PIDR <sub>y</sub> = 0.39% | – |
|    | 18 | W2.42 | – | PIDR <sub>x</sub> = 0.89%, PIDR <sub>y</sub> = 0.51% | I |
|    | 17 | W2.51 | – | PIDR <sub>x</sub> = 0.59%, PIDR <sub>y</sub> = 0.38% | – |
|    | 18 | W2.52 | – | PIDR <sub>x</sub> = 0.91%, PIDR <sub>y</sub> = 0.34% | I |
|    | 17 | W2.61 | – | PIDR <sub>x</sub> = 0.54%, PIDR <sub>y</sub> = 0.41% | – |
|    | 18 | W2.62 | – | PIDR <sub>x</sub> = 0.87%, PIDR <sub>y</sub> = 0.32% | I |
|    | 17 | W2.71 | – | PIDR <sub>x</sub> = 0.51%, PIDR <sub>y</sub> = 0.52% | – |
|    | 18 | W2.72 | – | PIDR <sub>x</sub> = 0.79%, PIDR <sub>y</sub> = 0.37% | I |

W2.01: No damage.

W2.02: (1) < 5.1 cm crack at west window opening and (1) > 15.2 cm crack at wall panel-to-panel interface (L3).

W2.11: No damage.

W2.12: (3) < 5.1 cm cracks at east window opening (L4).

W2.21: No damage.

W2.22: (4) < 5.1 cm cracks at window openings (L5).

W2.31: No damage.

W2.32: (1) > 20.3 cm crack and (3) < 5.1 cm cracks at window openings (L6).

W2.41: No damage.

W2.42: (1) > 15.2 cm crack and (5) < 5.1 cm cracks at window openings. (2) < 5.1 cm caulking cracks at floor-to-floor interface (L7).

W2.51: No damage.

W2.52: (1) > 22.9 cm crack, (2) > 7.6 cm cracks and (2) < 5.1 cm cracks at window openings (L8).

W2.61: No damage.

W2.62: (1) 10.2-12.7 cm crack and (1) < 5.1 cm crack at west window opening (L9).

W2.71: No damage.

W2.72: (1) > 15.2 cm crack, (1) 5.1-7.6 cm crack, (1) 12.7-15.2 cm crack, (2) < 5.1 cm cracks at window openings. (1) < 5.1 cm crack on the surface (L10).

|    |    |       |                     |                                                      |   |
|----|----|-------|---------------------|------------------------------------------------------|---|
| S1 | 18 | S1.01 | –                   | PIDR <sub>x</sub> = 0.33%, PIDR <sub>y</sub> = 0.24% | – |
|    | 18 | S1.11 | –                   | PIDR <sub>x</sub> = 0.48%, PIDR <sub>y</sub> = 0.46% | – |
|    | 17 | S1.21 | –                   | PIDR <sub>x</sub> = 0.51%, PIDR <sub>y</sub> = 0.41% | I |
|    | 17 | S1.22 | S1.21, not repaired | PIDR <sub>x</sub> = 0.51%, PIDR <sub>y</sub> = 0.50% | – |
|    | 17 | S1.31 | –                   | PIDR <sub>x</sub> = 0.59%, PIDR <sub>y</sub> = 0.66% | – |
|    | 17 | S1.41 | –                   | PIDR <sub>x</sub> = 0.69%, PIDR <sub>y</sub> = 0.44% | I |
|    | 18 | S1.42 | S1.41, repaired     | PIDR <sub>x</sub> = 0.67%, PIDR <sub>y</sub> = 0.49% | I |
|    | 18 | S1.51 | –                   | PIDR <sub>x</sub> = 0.69%, PIDR <sub>y</sub> = 0.44% | – |
|    | 17 | S1.61 | –                   | PIDR <sub>x</sub> = 0.63%, PIDR <sub>y</sub> = 0.39% | I |
|    | 18 | S1.62 | S1.61, not repaired | PIDR <sub>x</sub> = 0.89%, PIDR <sub>y</sub> = 0.51% | – |
|    | 17 | S1.71 | –                   | PIDR <sub>x</sub> = 0.59%, PIDR <sub>y</sub> = 0.38% | – |
|    | 18 | S1.72 | –                   | PIDR <sub>x</sub> = 0.91%, PIDR <sub>y</sub> = 0.34% | – |
|    | 17 | S1.81 | –                   | PIDR <sub>x</sub> = 0.54%, PIDR <sub>y</sub> = 0.41% | – |
|    | 18 | S1.82 | –                   | PIDR <sub>x</sub> = 0.87%, PIDR <sub>y</sub> = 0.32% | – |

S1.01: No damage at L1.

S1.11: No damage at L2.

S1.21: Handrail rigid (continuous) connection fracture at L3.

S1.22: No repair before test. No new damage.

S1.31: No damage at L4.

S1.41: Handrail hinged and sliding connection pull-out at L5.5.

S1.42: Prior damage repaired before test. New damage: handrail hinged and sliding connection detachment.

S1.51: No damage at L6.

S1.61: Handrail slip-fit connection distortion at L7.5.

S1.62: No repair before test. No new damage.

S1.71, S1.72: No damage at L8.

S1.81, S1.82: No damage at L9

|    |    |       |   |                           |   |
|----|----|-------|---|---------------------------|---|
| X1 | 17 | X1.01 | – | PIDR <sub>y</sub> = 0.32% | I |
|    | 18 | X1.11 | – | PIDR <sub>y</sub> = 0.46% | – |
|    | 18 | X1.21 | – | PIDR <sub>y</sub> = 0.50% | – |
|    | 18 | X1.31 | – | PIDR <sub>y</sub> = 0.44% | – |
|    | 17 | X1.41 | – | PIDR <sub>y</sub> = 0.41% | – |

X1.01: Level 2, Line C door (open) frame hinge damage, but operational.

X1.11: No damage to Level 2, Line D door (closed).

X1.21: No damage to Level 3, Line D and E doors (closed).

X1.31: No damage to Level 6, Line D and E doors (closed).

X1.41: No damage to Level 9, Line D door (closed).

|                   |    |       |   |                           |   |
|-------------------|----|-------|---|---------------------------|---|
| X2                | 18 | X2.01 | – | PIDR <sub>x</sub> = 0.48% | – |
| X2.01: No damage. |    |       |   |                           |   |
| X3                | 18 | X3.01 | – | PIDR <sub>x</sub> = 0.69% | – |
| X3.01: No damage. |    |       |   |                           |   |
| X4                | 18 | X4.01 | – | PIDR <sub>x</sub> = 0.79% | – |
| X4.01: No damage. |    |       |   |                           |   |
| X5                | 18 | X5.01 | – | PIDR <sub>x</sub> = 0.91% | – |
| X5.01: No damage. |    |       |   |                           |   |
| X6                | 18 | X6.01 | – | PIDR <sub>x</sub> = 0.69% | – |
| X6.01: No damage. |    |       |   |                           |   |
| X7                | 18 | X7.01 | – | PIDR <sub>x</sub> = 0.91% | – |
| X7.01: No damage. |    |       |   |                           |   |
| X8                | 17 | X8.01 | – | PIDR <sub>x</sub> = 0.69% | – |
| X8.01: No damage. |    |       |   |                           |   |

I = Inconsequential, C = Consequential.



**Table 4: Observations for NCSs (ASCE 7-22, Section 13.6) from seismic tests.**

| NCS ID                                                                                        | MID | Damage description | Prior damage        | EDP                                                                          | Damage class |
|-----------------------------------------------------------------------------------------------|-----|--------------------|---------------------|------------------------------------------------------------------------------|--------------|
| F1                                                                                            | 18  | F1.01              | –                   | PFA <sub>L</sub> = 0.99g, PFA <sub>T</sub> = 0.61g, PFA <sub>z</sub> = 0.45g | –            |
|                                                                                               |     | F1.02              | –                   | PFA <sub>L</sub> = 0.58g, PFA <sub>T</sub> = 1.18g, PFA <sub>z</sub> = 0.40g | –            |
|                                                                                               | 17  | F1.03              | –                   | PFA <sub>L</sub> = 0.71g, PFA <sub>T</sub> = 0.83g, PFA <sub>z</sub> = 0.13g | –            |
|                                                                                               | 18  | F1.04              | –                   | PFA <sub>L</sub> = 0.41g, PFA <sub>T</sub> = 0.95g, PFA <sub>z</sub> = 0.37g | –            |
|                                                                                               |     | F1.05              | –                   | PFA <sub>L</sub> = 0.79g, PFA <sub>T</sub> = 0.43g, PFA <sub>z</sub> = 0.46g | –            |
|                                                                                               | 17  | F1.06              | –                   | PFA <sub>L</sub> = 0.49g, PFA <sub>T</sub> = 0.69g, PFA <sub>z</sub> = 0.06g | –            |
|                                                                                               | 18  | F1.07              | –                   | PFA <sub>L</sub> = 0.92g, PFA <sub>T</sub> = 0.38g, PFA <sub>z</sub> = 0.09g | –            |
| F1.01-F1.07: No damage.                                                                       |     |                    |                     |                                                                              |              |
| F2                                                                                            | 17  | F2.01              | –                   | PFA <sub>L</sub> = 1.34g, PFA <sub>T</sub> = 1.34g, PFA <sub>z</sub> = 0.31g | –            |
|                                                                                               | 18  | F2.02              | –                   | PFA <sub>L</sub> = 0.92g, PFA <sub>T</sub> = 1.81g, PFA <sub>z</sub> = 0.37g | –            |
| F2.01-F2.02: No damage.                                                                       |     |                    |                     |                                                                              |              |
| F3                                                                                            | 17  | F3.01              | –                   | PFA <sub>L</sub> = 0.97g, PFA <sub>T</sub> = 1.64g, PFA <sub>z</sub> = 0.26g | –            |
|                                                                                               | 18  | F3.02              | –                   | PFA <sub>L</sub> = 0.71g, PFA <sub>T</sub> = 1.75g, PFA <sub>z</sub> = 0.39g | –            |
| F3.01-F3.02: No damage.                                                                       |     |                    |                     |                                                                              |              |
| F4                                                                                            | 16  | F4.01              | –                   | PIDR <sub>x</sub> = 0.31%, PIDR <sub>y</sub> = 0.21%                         | I            |
|                                                                                               | 18  | F4.02              | F4.01, not repaired | PIDR <sub>x</sub> = 0.91%, PIDR <sub>y</sub> = 0.34%                         | –            |
|                                                                                               | 17  | F4.11              | –                   | PIDR <sub>x</sub> = 0.59%, PIDR <sub>y</sub> = 0.66%                         | I            |
|                                                                                               | 18  | F4.21              | –                   | PIDR <sub>x</sub> = 0.67%, PIDR <sub>y</sub> = 0.49%                         | I            |
| F4.01: No leakage. Slip at floor clamps at L8.5 of ~20 mm, riser pipe not perfectly vertical. |     |                    |                     |                                                                              |              |
| F4.02: No repair before test. No new damage.                                                  |     |                    |                     |                                                                              |              |
| F4.11: No leakage. Slip at floor clamps at L4.5 of ~10 mm, riser pipe not perfectly vertical. |     |                    |                     |                                                                              |              |
| F4.11: No leakage. Slip at floor clamps at L5.5 of ~12 mm, riser pipe not perfectly vertical. |     |                    |                     |                                                                              |              |
| F5                                                                                            | 18  | F5.01              | –                   | PIDR <sub>y</sub> = 0.50%                                                    | –            |
|                                                                                               | 17  | F5.11              | –                   | PIDR <sub>y</sub> = 0.41%                                                    | –            |
|                                                                                               |     | F5.12              | –                   | PFA <sub>x</sub> = 0.76g, PFA <sub>y</sub> = 0.52g, PFA <sub>z</sub> = 0.14g | –            |
|                                                                                               | 18  | F5.13              | –                   | PFA <sub>x</sub> = 0.98g, PFA <sub>y</sub> = 0.49g, PFA <sub>z</sub> = 0.19g | –            |
| F5.01, F5.11-F5.13: No damage.                                                                |     |                    |                     |                                                                              |              |
| F6                                                                                            | 18  | F6.01              | –                   | PIDR <sub>y</sub> = 0.46%                                                    | –            |
|                                                                                               | 18  | F6.11              | –                   | PIDR <sub>y</sub> = 0.44%                                                    | –            |
| F6.01, F6.11: Minor twisting under gypsum board, no damage.                                   |     |                    |                     |                                                                              |              |
| G1                                                                                            | 17  | G1.01              | –                   | PFA <sub>L</sub> = 0.83g, PFA <sub>T</sub> = 1.31g, PFA <sub>z</sub> = 0.30g | –            |
|                                                                                               | 18  | G1.02              | –                   | PFA <sub>L</sub> = 0.78g, PFA <sub>T</sub> = 1.83g, PFA <sub>z</sub> = 0.28g | –            |
|                                                                                               | 17  | G1.11              | –                   | PFA <sub>L</sub> = 1.44g, PFA <sub>T</sub> = 1.59g, PFA <sub>z</sub> = 0.33g | –            |
|                                                                                               | 18  | G1.12              | –                   | PFA <sub>L</sub> = 0.99g, PFA <sub>T</sub> = 2.02g, PFA <sub>z</sub> = 0.35g | –            |
|                                                                                               | 17  | G1.21              | –                   | PFA <sub>L</sub> = 0.54g, PFA <sub>T</sub> = 0.76g, PFA <sub>z</sub> = 0.11g | –            |
|                                                                                               | 18  | G1.31              | –                   | PFA <sub>L</sub> = 0.70g, PFA <sub>T</sub> = 0.75g, PFA <sub>z</sub> = 0.17g | –            |
| G1.01-G1.02: No damage.                                                                       |     |                    |                     |                                                                              |              |
| G1.11-G1.12: No damage. ~8 mm slip of gravity hanger.                                         |     |                    |                     |                                                                              |              |
| G1.21: No damage.                                                                             |     |                    |                     |                                                                              |              |
| G1.31: No damage.                                                                             |     |                    |                     |                                                                              |              |
| G2                                                                                            | 18  | G1.01              | –                   | PFA <sub>L</sub> = 1.36g, PFA <sub>T</sub> = 1.30g, PFA <sub>z</sub> = 0.35g | –            |
|                                                                                               | 17  | G1.11              | –                   | PFA <sub>L</sub> = 1.35g, PFA <sub>T</sub> = 1.49g, PFA <sub>z</sub> = 0.25g | –            |
|                                                                                               | 18  | G1.12              | –                   | PFA <sub>L</sub> = 0.97g, PFA <sub>T</sub> = 1.83g, PFA <sub>z</sub> = 0.34g | –            |
|                                                                                               | 17  | G1.21              | –                   | PFA <sub>L</sub> = 0.63g, PFA <sub>T</sub> = 0.62g, PFA <sub>z</sub> = 0.11g | –            |
|                                                                                               | 17  | G1.31              | –                   | PFA <sub>L</sub> = 0.63g, PFA <sub>T</sub> = 0.66g, PFA <sub>z</sub> = 0.15g | –            |
| G1.01: No damage.                                                                             |     |                    |                     |                                                                              |              |

G1.11-G1.12: No damage.

G1.21: No damage.

G1.31: No damage.

|                                                                                                    |    |       |                     |                                                                              |   |
|----------------------------------------------------------------------------------------------------|----|-------|---------------------|------------------------------------------------------------------------------|---|
| M1                                                                                                 | 16 | M1.01 | –                   | PFA <sub>x</sub> = 0.92g, PFA <sub>y</sub> = 0.84g, PFA <sub>z</sub> = 0.38g | – |
|                                                                                                    | 17 | M1.02 | –                   | PFA <sub>x</sub> = 1.54g, PFA <sub>y</sub> = 1.02g, PFA <sub>z</sub> = 0.53g | C |
|                                                                                                    | 18 | M1.03 | M1.02, repaired     | PFA <sub>x</sub> = 1.92g, PFA <sub>y</sub> = 0.82g, PFA <sub>z</sub> = 0.56g | – |
| M1.01: No damage.                                                                                  |    |       |                     |                                                                              |   |
| M1.02: One self-drilling screw of anchorage ruptured.                                              |    |       |                     |                                                                              |   |
| M1.03: Prior damage repaired by installing a CFS support clip before the test. No new damage.      |    |       |                     |                                                                              |   |
| M2                                                                                                 | 18 | M2.01 | –                   | PFA <sub>x</sub> = 1.82g, PFA <sub>y</sub> = 0.93g, PFA <sub>z</sub> = 0.56g | – |
| M2.01: No damage.                                                                                  |    |       |                     |                                                                              |   |
| M3                                                                                                 | 16 | M3.01 |                     | PFA <sub>x</sub> = 0.98g, PFA <sub>y</sub> = 0.74g, PFA <sub>z</sub> = 0.10g | – |
|                                                                                                    | 17 | M3.02 |                     | PFA <sub>x</sub> = 1.60g, PFA <sub>y</sub> = 1.03g, PFA <sub>z</sub> = 0.17g | I |
|                                                                                                    | 18 | M3.03 | M3.02, not repaired | PFA <sub>x</sub> = 1.97g, PFA <sub>y</sub> = 0.84g, PFA <sub>z</sub> = 0.23g | I |
| M3.01: No damage.                                                                                  |    |       |                     |                                                                              |   |
| M3.02: Localized deformation of anchorage.                                                         |    |       |                     |                                                                              |   |
| M3.03: No repair before the test. Localized deformation of anchorage, bending of one support rack. |    |       |                     |                                                                              |   |
| M4                                                                                                 | 18 | M4.01 | –                   | PFA <sub>x</sub> = 1.98g, PFA <sub>y</sub> = 0.86g, PFA <sub>z</sub> = 0.23g | – |
| M4.01: No damage.                                                                                  |    |       |                     |                                                                              |   |
| M5                                                                                                 | 18 | M5.01 | –                   | PFA <sub>x</sub> = 1.91g, PFA <sub>y</sub> = 0.91g, PFA <sub>z</sub> = 0.56g | – |
| M5.01: No damage.                                                                                  |    |       |                     |                                                                              |   |

I = Inconsequential, C = Consequential. Note PFA<sub>L</sub> and PFA<sub>T</sub> are measured floor accelerations along the longitudinal and transverse directions of the component, respectively.

**Table 5: Observations for NCSs from fire tests.**

| NCS ID                                                                                                                                                                                                                          | Test ID | Damage description | Nearest measured peak temperature [°C] | Damage class |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|--------------------|----------------------------------------|--------------|
| C3                                                                                                                                                                                                                              | 1       | C3.51              | 506                                    | C            |
|                                                                                                                                                                                                                                 | 2       | C3.61              | 875                                    | C            |
| C3.51, C3.62: Most ceiling gypsum boards severely damaged in fire.                                                                                                                                                              |         |                    |                                        |              |
| W1                                                                                                                                                                                                                              | 1       | W1.51              | 548                                    | C            |
|                                                                                                                                                                                                                                 | 2       | W1.61              | 534                                    | C            |
| W1.51, W1.61: Most wall gypsum boards severely damaged in fire.                                                                                                                                                                 |         |                    |                                        |              |
| W2                                                                                                                                                                                                                              | 1       | W2.81              | 944                                    | C            |
|                                                                                                                                                                                                                                 | 2       | W2.91              | –                                      | C            |
| W2.81, W2.91: EIFS layer damage due to fire emanating from window opening.                                                                                                                                                      |         |                    |                                        |              |
| X1                                                                                                                                                                                                                              | 1       | X1.51              | 1006                                   | C            |
|                                                                                                                                                                                                                                 | 1       | X1.61              | 1014                                   | C            |
|                                                                                                                                                                                                                                 | 2       | X1.71              | 1058                                   | C            |
|                                                                                                                                                                                                                                 | 2       | X1.81              | –                                      | C            |
| X1.51, X1.71: Door at Line D jammed, burnt interior door handle.                                                                                                                                                                |         |                    |                                        |              |
| X1.61, X1.81: Burnt interior door handle of door at Line E.                                                                                                                                                                     |         |                    |                                        |              |
| X7                                                                                                                                                                                                                              | 1       | X7.51              | 944                                    | C            |
| X7.51: Extensive cracking in exterior pane of L10 window, glazing movement 6 mm relative to window frame, frame distortion, jammed handle, inoperable window.                                                                   |         |                    |                                        |              |
| F1                                                                                                                                                                                                                              | 1       | F1.51              | 506                                    | C            |
|                                                                                                                                                                                                                                 | 2       | F1.61              | 875                                    | C            |
| F1.51, F1.61: Severe deformation due to thermal stresses, sprinkler drops severely damaged by fire.                                                                                                                             |         |                    |                                        |              |
| F5                                                                                                                                                                                                                              | 1       | F5.51              | 1006                                   | C            |
| F5.51: Fire-rated sleeve performed as designed, with some smoke allowed to emanate through. Portions of cables outside the fire compartment were protected from it, while the cable portions inside the compartment were burnt. |         |                    |                                        |              |

|                                                                                             |   |       |      |   |
|---------------------------------------------------------------------------------------------|---|-------|------|---|
| G1                                                                                          | 1 | G1.51 | 967  | C |
|                                                                                             | 2 | G1.61 | 833  | C |
| G1.51, G1.61: Visible permanent deformation due to thermal stresses.                        |   |       |      |   |
| G2                                                                                          | 1 | G2.51 | 946  | C |
|                                                                                             | 2 | G2.61 | 1058 | C |
| G2.51, G2.61: Sections of pipe (jacket and corrugated metal tube) severely damaged by fire. |   |       |      |   |
| I = Inconsequential, C = Consequential.                                                     |   |       |      |   |

From Tables 3 and 4, it can be seen that despite the demanding sequence of 18 earthquake tests, only one instance of consequential damage to NCSs was observed. Even though many instances of inconsequential damage are noted, these were aesthetical in nature and could be readily repaired. However, the severity of damage due to live fire compartment tests, as noted in Table 5, was significantly higher. The fires were aggressive in nature and allowed to naturally extinguish (> 90 min from ignition), resulting in large peak gas temperatures reaching 1000°C. As a result, all NCSs within and a story above the fire test compartments suffered consequential damage which would require extensive repair action.

## CONCLUSIONS

The CFS10 building, a 10-story cold-formed steel-framed structure, was tested at the 6-DOF Large High Performance Outdoor Shake Table (LHPOST6). The building was outfitted with a range of nonstructural components and systems (NCSs) such as fire sprinkler and gas piping systems, suspended ceilings, a resilient stair system, windows, swing and roll-up doors, roof-mounted mechanical equipment, architectural wall and ceiling finishes, and firestop and protection materials. This paper lists the physical test observations and correlates them with measured engineering demand parameters (EDP) such as floor acceleration, building inter-story drift or peak local temperature responses from the seismic and fire tests. The data presentation follows a similar schema used in Nonstructural Element Database (NED) developed by NIST and is organized per Sections 13.5 and 13.6 of ASCE 7-22. In this paper, test observations for NCSs are systematically organized to enable direct linkage to the fragility classifications defined in FEMA P-58. Combined with data from literature characterizing their performance, updated or entirely new fragility functions can be developed for these nonstructural components and systems. The functional recovery metrics such repair cost and time associated with damages presented in this paper will be discussed in future publications.

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