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ABSTRACT

The CFS-NHERI 10-Story Building Capstone Test Program, coined CFS10, offered an opportunity to demonstrate, through full-scale testing at NHERI@UC San Diego 6-DOF Large High-Performance Outdoor Shake Table (LHPOST6), the resiliency and robustness of cold-formed steel (CFS) framing, a material that has consistently shown such qualities in large scale and component-level tests. This unique test program brought together three widely used construction methods, namely, stick-framing, panelization (2D), and volumetric modularization (3D), allowing them to be directly compared within the same structure. Notably, a 9-story Modular Stair System (MSS) was also integrated into the structure. These stair modules, capable of supporting their own weight, significantly reduced construction time, which ultimately shaped the building's construction sequence and saved labor hours and site congestion

The layout of the 10-story specimen allowed each method to occupy its own section. The construction team needed to resolve a series of planning and coordination challenges. Building Information Modeling (BIM) facilitated this process and helped maintain smooth progress, as discussed in this paper. The result was a complete, test-ready structure that brings all three systems together in one place. While each method offered distinct benefits, the experience gained through the implementation of modular systems points toward a more controlled, efficient, and scalable path forward for CFS construction, with the potential to support more efficient construction of residential buildings.

INTRODUCTION

The construction industry is undergoing a long-awaited shift toward industrialized methods as it seeks to improve productivity, reduce costs, and meet growing housing demands. Modular and offsite construction have emerged as viable solutions, which offer greater efficiency, repeatability, and quality control compared to traditional site-built processes (Smith et al., 2023). Among the structural materials poised to benefit most from this transition is cold-formed steel (CFS), which offers high strength-to-weight ratios, seismic resilience, fire resistance, and compatibility with prefabrication. These attributes make CFS particularly well-suited for integration with panelized and volumetric modular construction (Islam et al., 2023).

Despite the growing body of research that highlights modularity's potential to scale industrialized building platforms (Islam et al., 2023), the adoption of such systems in mid- to high-rise seismic applications remains limited. This gap is partially due to a lack of comprehensive, full-scale experimental data validating their structural performance, especially under multi-directional dynamic loading. Concurrently, the development of modular design platforms in industrialized construction has emphasized more on product modularity than the complex process and on-site integration challenges that often arise in real modular projects (Islam et al., 2023).

To address these challenges, the landmark CFS-NHERI 10-Story Building Capstone Test Program, coined CFS10, which was aimed at designing and evaluating the performance of a beyond-code all CFS-framing system under earthquake loading, embraced the use of varying construction methods. Designed as an 11.6 m × 6.9 m x 10-story slice of an archetype residential building (Torabian et al., 2016). The CFS10 project incorporated three distinct construction methods: stick-framing (1D), panelization (2D), and volumetric (3D) modularization into a single structure. Figure 1 illustrates the 3D modular approach, with a prefabricated module being lifted into place. This enabled a unique, side-by-side comparison under identical structural and loading conditions, offering insights into their comparative constructability, integration issues, and seismic response.

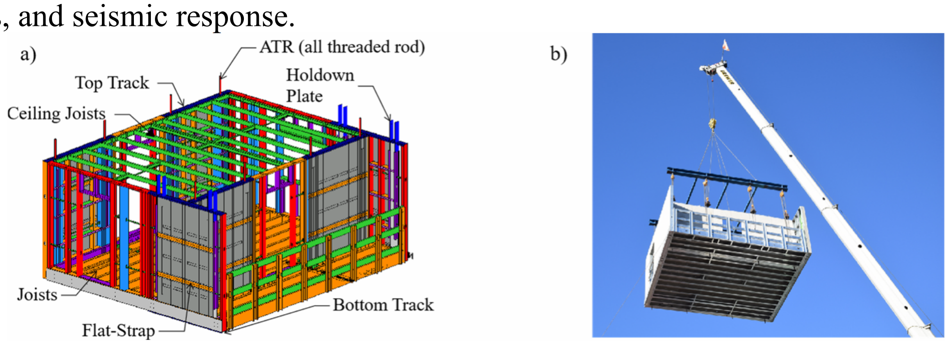

Figure 1. CFS10 volumetric module: (a) BIM model highlighting key framing elements, (b) module lifted by crane during field operations.

This paper presents detailed documentation of the planning, implementation, and coordination strategies used in the CFS10 project, focusing on the construction differences across the three methods. The aim is to assess the implications on installation workflows, field challenges, and performance outcomes. This study contributes to ongoing efforts to validate modular and prefabricated CFS construction approaches as viable, scalable solutions for resilient mid-rise housing in seismic zones.

PROJECT CONSTRUCTION OVERVIEW

The CFS-NHERI 10-Story Building Capstone Test Program, (CFS10), features a full-scale test structure with a floor plan of 11.6 m × 6.9 m, a standard story height of 3.05 m across ten stories, and a 1.1 m tall parapet, resulting in a building with a total height of 31.6 m. It employs steel sheet sheathed shear walls in each orthogonal direction to serve as the lateral force-resisting system; however, with varying chord system details, namely: a tie rod system along (6) north–south walls and a hold-down system along (4) east–west walls. The CFS10 building represents a slice of an archetype residential building, with each level divided into east and west units, both consisting of a room and a balcony (which is the beginning of the next room in the full archetype building). Stair modules were stacked at Level 1-9 to support egress/ingress into the building, while access to Level 11 (roof) was facilitated via a ships-ladder and access hatch. Additional details of the structural and nonstructural design are available in Singh et al. (2022, 2024), Sorosh et al. (2025), and Hutchinson et al. (2026). The seismic tests were recently completed in summer 2025, with select initial findings presented in this same conference (Hutchinson et al., 2026).

One advantage of CFS is its versatility: lightweight, screw-fastened framing is forgiving and customizable, allowing ready adaptation to the construction methods used in this project, see Figure 2.

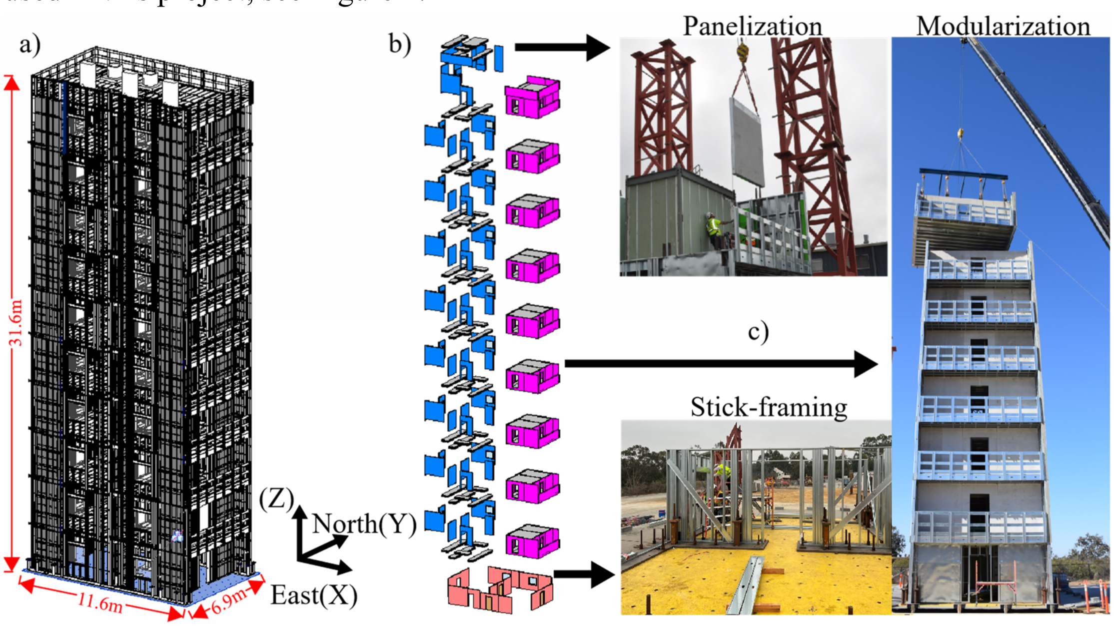

Figure 2**.** (a) CFS10 structure (Revit model), (b) construction methods breakdown, and (c) representative field installation photos of stick framing, panelization, and modularization.

Stick Framing (1D) is the most traditional and flexible method, with elements installed directly on site per project drawings. Stick framing is customizable, but less efficient, as it involves extended on-site assembly and greater exposure to unforeseen conditions compared to controlled environments. Stick framing was used on the first floor of the building to handle the complex integration with the shake table platen.

Panelization (2D) consists of walls and floors manufactured as 2D panels in a controlled off-site environment, improving quality and consistency. Predefined layouts improve trade coordination, reduce clashes, and minimize field issues during installation. Shipping is also straightforward for panelization. Panelization is the dominant construction method in CFS-framing today and was utilized for the west rooms for stories 2-10 of CFS10.

Volumetric Modularization (3D) is a relatively new method where partially or fully finished units are built in a controlled environment, either on- or off-site, and, if constructed off-site, delivered ready for installation, resembling a toy block set. Modular construction enables repeatable, assembly-line production, reducing on-site labor and uncertainty while offering greater quality and schedule control. On-site modularization was employed for the east rooms for stories 2–10 of CFS10.

CFS10 was a complex, real, building – far from a typical test specimen. The construction effort was supported by a variety of needed experts. BIM coordination and modeling provided the shop drawings and clash checks needed for stick-framed, panelized, and modular sections. Fabrication specialists assembled CFS profiles into wall and floor panels off-site, while modular units were assembled in parallel with site activities. Field crews erected the building by first completing the stick-framed portion of the first level, followed by stair module installation on the west side, setting the modular unit on the east side, and finally, installing the prefabricated panels on the west side.

PLANNING THE CONSTRUCTION APPROACHES

Stick and Prefabricated Components – The first floor was selected to be stick-framed to ease attachment to the shake table platen, see Figure 3. Transfer plates were anchored to the platen with shear anchors, post-tensioned rods (at shear wall ends), hollow structural section (HSS) steel tubes, square plates, and the first-level bottom tracks were fastened to these plates with power actuated fasteners (PAFs).

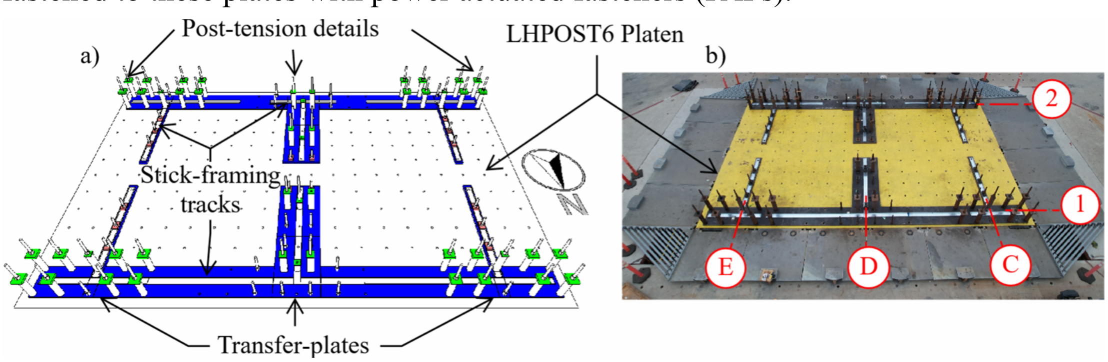

Figure 3. CFS10-LHPOST6 base transfer plate details: (a) BIM model (b) aerial site view

The six north-south direction shear walls were detailed with tie rods threaded either directly into the table (lines C and E) or to attachment HSS stubs (line D). All tie-rods continued vertically as part of the designed lateral force-resisting system. In contrast, the four east-west direction shear walls were detailed with HSS tubes directly welded to the transfer plates. West rooms on levels 2–10 used panelization around the stair modules; with ledger-hung floors with joists spanning north-south direction, floor panels closed the level below as wall panels erected the level above. Figure 4 shows the distribution of prefabricated components in the CFS10 building by level. In this layout, F-# denotes floor assemblies and W-# denotes wall assemblies where rectangular callouts identify panelized assemblies and oval callouts identify modular ones. For clarity, ceilings are not displayed in the figure, though in the actual module, they were located above F-6 and F-7, with ceiling joists spanning perpendicular to the floor joists. Ceiling joists were designed into the modular space only, largely to serve as the top of the modular unit. The dimensions of each component were shaped by project-specific factors such as window, door, and stair openings, with floors segmented and designed to fit around the stair modules during erection. Practical considerations, such as manageable transportation, guided the maximum panel sizes, since roadway lanes between the fabrication site and the shake table limited what could be delivered. Constructability was tied to hoisting and placement, as the substantial panel weights directly affected erection, see Figure 5. Performance guided the detailing, with panels arranged as symmetrically as possible to balance weight and stiffness across the structure. Despite these efforts, stair openings and heavier stair units created eccentricities, which were addressed by strategically adding supplemental weight at each floor (varying amount and location on floor plan) to minimize the offset in the center of mass and center of stiffness.

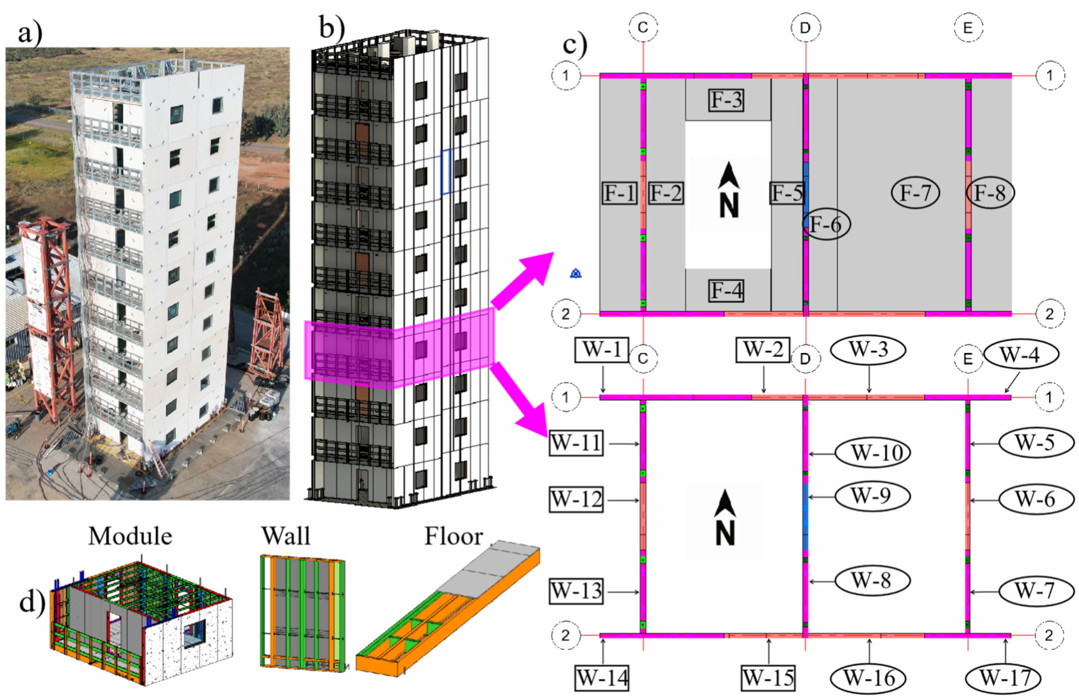

Figure 4. CFS10 assembly layout: (a) full-scale specimen; (b) BIM model; (c) floor plan arrangement, rectangular-panelized, oval-modular; (d) representative assemblies (ceiling assemblies not shown for clarity).

Figure 5 compiles the weights of the prefabricated components, bringing together floor panels of 1.5–4.5 kN, roof panels of 2.4–10.1 kN, wall panels varying from 0.7–10.6 kN, and modular walls ranging between 0.8–8.8 kN. At the larger scale, fully assembled volumetric modules weighed between 66– 91 kN. This range illustrates both the diversity of prefabricated elements and the lightweight characteristics of CFS, where even complete modules remain within practical lifting capacities.

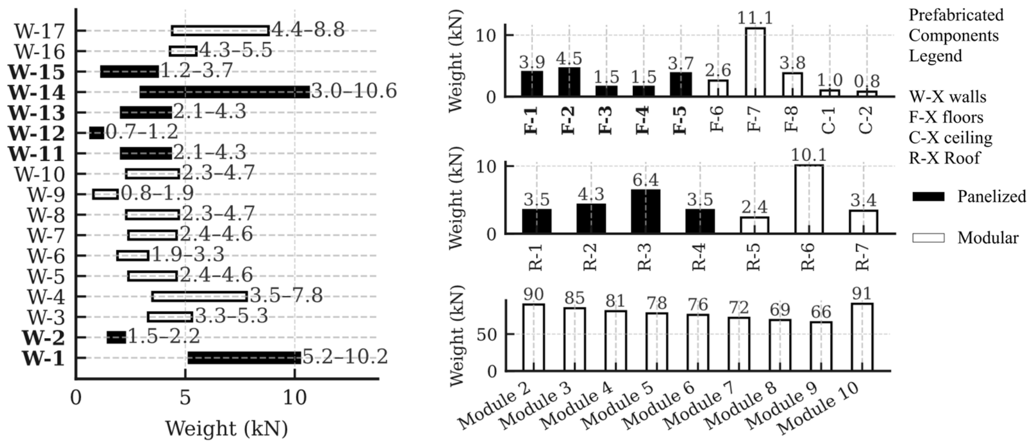

Figure 5. Prefabricated components' weights. Note that (3D) modules were assembled on-site from the noted floor and wall panels, modules start at 2 given that first level was stick-framing.

Redesigning for Modular – To incorporate the modular concept into CFS10, adaptations were required from the original design. BIM coordination and modeling were essential in planning strategies for modular (3D) adaptation. By testing different concepts and visualizing them in the model, advantages and limitations were identified, leading to the level-by-level integration shown in Figure 2 as the most suitable approach for the project. The adaptation to modular construction introduced a series of challenges that required close coordination. Some were identified early, while others emerged as unintended consequences of implemented solutions. All were analyzed and addressed through the 3D BIM model, which remained central to navigating this evolving process. The following coordination issues illustrate both interdependent and stand-alone challenges resolved during implementation.

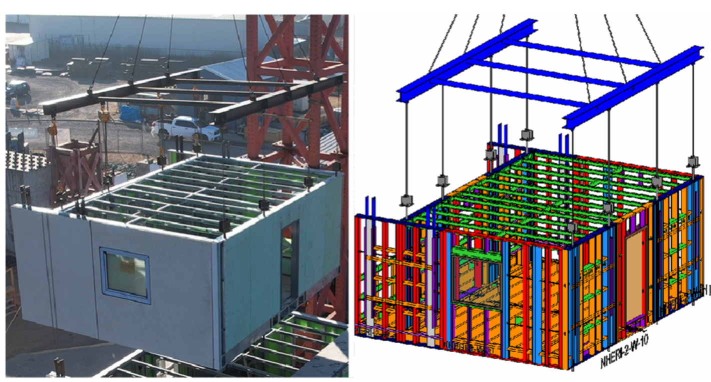

Figure 6. Module 3 lift shown in on-site operation (left) and BIM model representation (right).

To approximate real-world conditions, the six-sided module (Figure 6) was designed with the floor placed at the bottom. This configuration allowed a conventional diaphragm design to be preserved, and the ceiling to function as a drop ceiling. To ensure structural rigidity during the module lift process, ceiling joists were oriented perpendicular to the floor joists. However, this approach eliminated the ledger-hung floor design on the modular side, introducing an elevation difference between the panelized and modular portions, as shown in Figure 7. The resulting elevation difference created a diaphragm discontinuity, which risked generating undesirable stress concentrations around the module studs. To mitigate this, a continuous row of blocking in the wall assemblies was added at the diaphragm edge. It is noted that this elevation difference did not create a final floor elevation variation between the module and panel sides of the building.

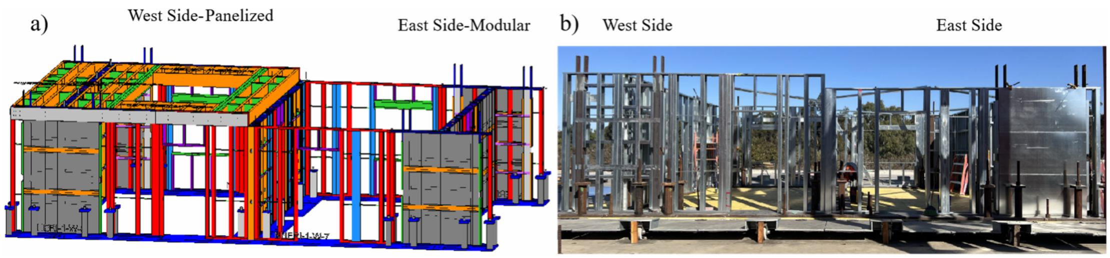

Figure 7. Modular-panelized level difference: (a) BIM model, (b) on-site condition

As the blocking had to be installed flush with the diaphragm's top surface, the space beneath it became inaccessible, complicating the connectivity of lateral force-resisting elements between subsequent modules. The tie-rod system was adjusted by raising the elevation of the couplers, while the hold-down system for the adjacent blockings of the endposts had two conditions, see Figure 8. Condition (1) in which hold-down plates were used (levels 2-6), blocking was replaced by a flat strap, and the plates were slid up to allow welding access. Originally designed for side fillet welds, the plates were modified to include a top-access slit for a plug weld to maintain connection strength. For hold-down brackets (levels 7-10), the blockings received a customized cut and were installed in the field after placement of the hold-down; the blocking action remained effective, as the cut did not compromise the stiffness required for load transfer.

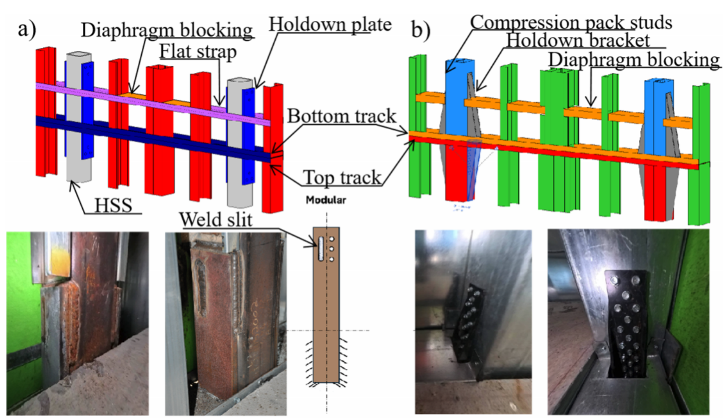

Figure 8. Hold-down system for module-module connections (a) hold-down plates and (b) hold-down brackets.

In parallel with these modifications, a module lifting strategy was developed. The system was required to ensure both robust load transfer for structural integrity and safe handling during lifting. The tie rod system provided eight strategically located all-thread rod (ATR) points, which were adapted for lifting, see Figure 9. To achieve a level and stable lift, the proposed solution was a steel lifting frame with eight pickup points for chain connections. The lifting frame and associated hardware were designed and implemented by the research team. Each chain was attached to an adaptor designed to engage the varied sized ATRs, enabling a pure vertical lift and providing the stability required under mildly windy conditions**.**

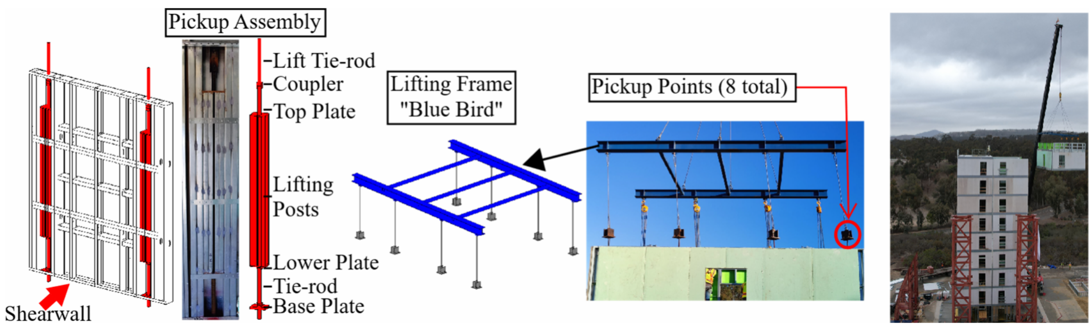

Figure 9. Modular pickup assembly showing lifting posts, tie-rod and plate connections in the BIM model, contrasted with on-site lifting using the eight-point frame.

MODULAR STAIR SYSTEM (MSS)

As part of this landmark 10-story cold-formed steel building, a 9-story prefabricated steel scissor-style stair tower was incorporated. The stair tower was located on the west side of the building, with the stairs transverse (weak) axis parallel to the X-axis of the building and the stair strong axis parallel to the Y-axis of the building. As shown in Figure 10, an individual story of stairs was assembled as a modular stair system unit (MSS). The MSS units were prefabricated, pre-assembled off of the building, with major components prefabricated off-site.

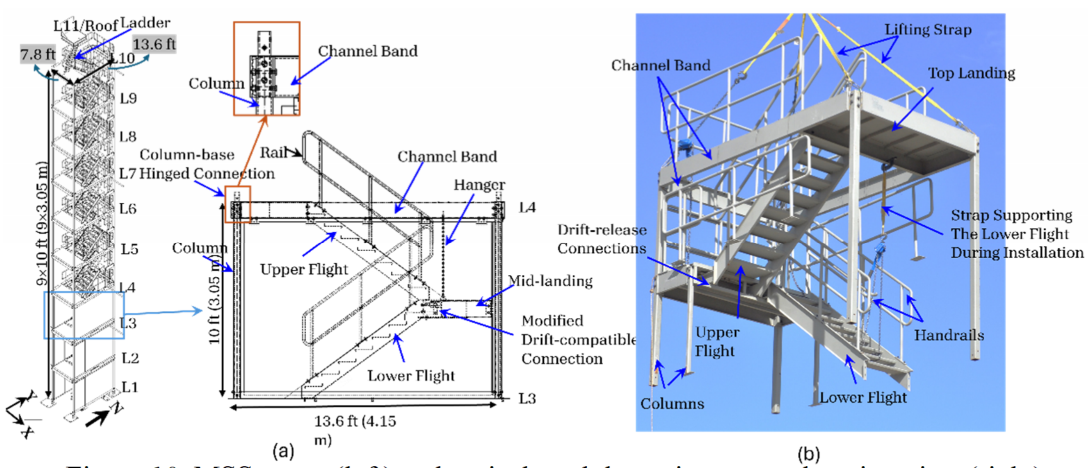

Figure 10. MSS tower (left) and typical modular stair system elevation view (right)

All units were installed as one complete MSS story. Each stair unit was a self-supporting module with hinged connections at the base of the stair columns. These columns consisted of vertical HSS that spanned floor to floor and support the gravity load of the stair channel band and landings. In traditional construction methods, commonly referred to as stick-framed, stairs lack these continuous vertical elements. Therefore, scaffolding or other temporary support around stair openings during construction is required. In contrast, MSSs are self-supporting and installed as complete units, eliminating the need for such temporary works. The use of the modularity concept in the stair system design resulted in reduced construction time and improved control over stair-to-diaphragm construction tolerances. In modular construction, MSS units can be installed either before or after the floor diaphragm and other structural elements, offering increased flexibility in the construction process. Moreover, they can be stacked multiple units at a time.

CONSTRUCTION PROCESS

Virtual Design and Coordination Phase - The coordination phase consisted of providing continuous model-based support to resolve interface issues, foresee potential clashes, and adapt sequencing strategies. BIM tools were used to generate panel layouts, placement plans, and connection details, which led to the project's smooth execution. Designers and fabricators, led by the BIM model led to the success of the program.

Stick-Framed/Panel Installation Phase - Work began at the shake-table platen interface: bottom tracks were anchored to the platen, and the designated lateral force-resisting elements were fixed to the base. With the interface established, first-floor stick framing started on Line D, and the other lines followed its layout. Once all walls were in, the west stair and the west-side floor panels were installed. Panelized construction then advanced level-by-level along the west elevation following a consistent sequence: perimeter wall panels W-15 through W-11 together with W-1 and W-2 were set to establish the plan, after which the next-level floor panels were flown. This cadence aligned crane picks and supported the staggered construction pace across stories.

Modular Assembly Phase - In this phase, the volumetric units were assembled adjacent to the main structure using a pony-wall stand as a temporary base. Due to the tight framing tolerances, especially around intersections and interior corners, the initial assembly sequence was refined through early adjustments to ensure all components could be placed without interference. Each module was constructed from the bottom up, beginning with floor panels to establish a stable base. Wall panels were then installed in a sequence that allowed clear access for fastening and alignment. Once the enclosure was complete, ceiling and diaphragm elements were added to finalize the unit. This process allowed the team to avoid rework during assembly and ensured that modules remained within tolerance for lifting and placement.

Lifting the modules demanded a high level of precision. The first lift set the precedent for all subsequent placements, refining the process through execution. To provide the required stability during lifting, four of the eight chains had to be adjustable, allowing the frame to compensate for any imbalances. Additionally, two guide cables were attached to each module to assist with alignment during hoisting. The modules were lifted slowly and steadily into position. Once placed, the crew inside the structure connected the tie rods from the lower level to the incoming module, securing its position and enabling the remaining structural and diaphragm connections to proceed.

Construction Sequence - To maintain a smooth construction flow, a sequence was planned that leveraged the advantages of each type of construction, see Figure 11. It began with the placement of the bottom tracks over the transfer plates, followed by the stick-framing of the first floor, which served as the structural base for the rest of the building. From there, the construction sequence was established: stair modules were installed first, always extending one level above the upcoming volumetric modules. Once the stair module was in place, the corresponding volumetric module was lifted and positioned alongside it, forming the east room. With the module secured, wall and floor panels were installed to complete the west room and the level's enclosure. This procedure, stair, module, then panels, not only balanced speed with control, but also created a continuous workflow. As soon as a module was lifted into place, the next one was being assembled, while panel installation proceeded in parallel. This overlapping pace allowed the teams to maintain momentum and keep construction moving steadily from level to level all the way to the tenth floor.

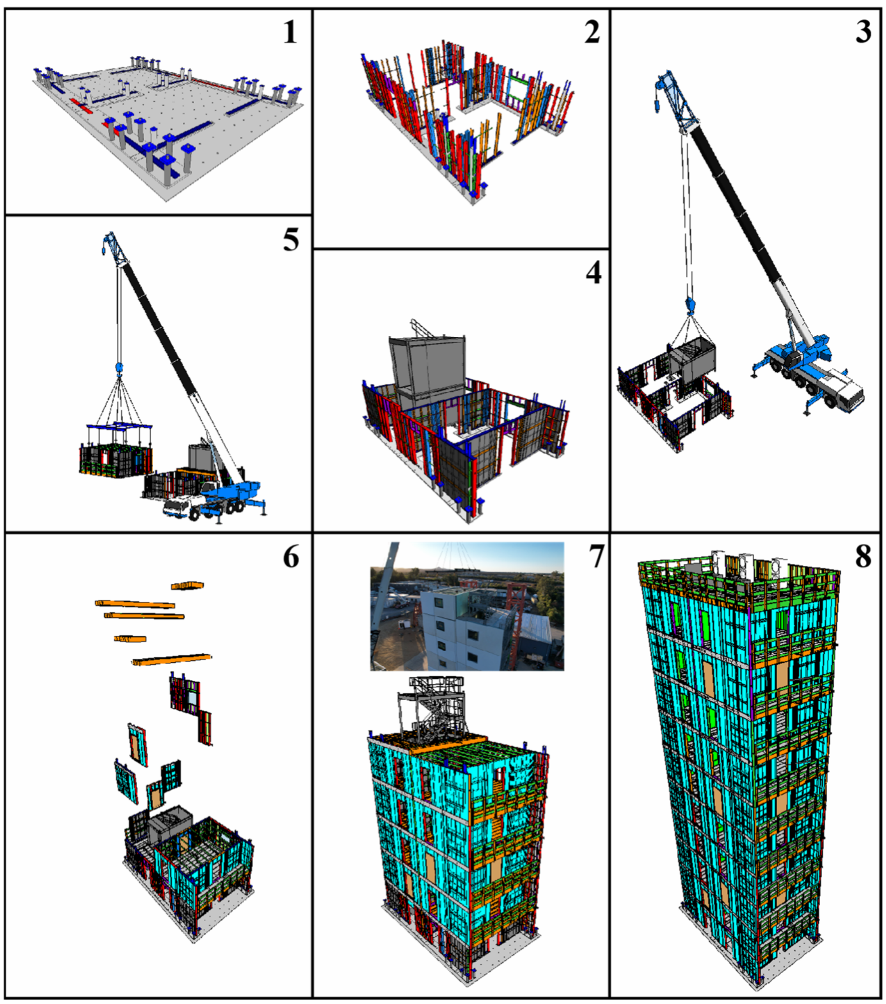

Figure 11. CFS10 construction sequence.

The gypsum board finishes within interior assemblies were deferred until after structural installation to allow the crew to complete the connections and other details required for load transfer. Once the structure was complete, gypsum finishes, and suspended ceilings were installed throughout the building.

INSTALLATION OVERVIEW AND DISCUSSION

The times presented in Table 1 correspond to on-site installation durations, defined as the period required for the field crew to flight, set, align, connect, and secure components for each construction method. These values capture on-site work only and exclude panel or module fabrication, off-site preassembly, and shop work. This phase is critical because extended on-site work escalates costs, increases safety exposure, and heightens vulnerability to site and environmental uncertainties that lead to delays, productivity losses, and quality decline.

Table 1. Comparison of installation only time across construction methods

Construction Methods	LEVEL									
	1	2	3	4	5	6	7	8	9	10
Stick-Framed	131h23	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Panelized	N/A	12h51	9h22	5h36	6h32	5h40	5h15	3h57	3h41	5h21
Modular		0h30	1h10	1h37	0h40	0h37	0h31	0h44	0h38	0h53

Another important factor is not only the duration each team requires to complete the work, but also the size of the crew involved in the installation. On average, the crews consisted of 4 for stick-framed, 5 for panelized, and 6 for modular. Using the installation times in Table 1 and the crew sizes, Table 2 presents the total man-hours required to complete the on-site installation of all CFS components in the CFS10 project for each construction method.

Table 2. Comparison of installation only man-hours across construction methods

Construction Methods	Stick-Framed	Panelized	Modular
Man-Hours	511.6	287.77	44.32

Installation metrics show clear differences across the three methods. On Level 1, crews spent 131 hours as the whole construction process was done on-site. Once the stick-framing was complete, subsequent levels showed the effect of industrialization. Panelized portions typically took 4-7 hours each, while modular units were set in about 30–100 minutes. Accounting for crew size, total installation only man-hours were 512 for stick-framed, 288 for panelized, and 44 for modular work. It is worth noting that panelization and modularization also require man-hours for their prefabrication; however, given the industrialization of their processes, the labor becomes more efficient. With these values, the focus is on **active installation**, specifically the portion most tied to cost, schedule risk, and workflow continuity; within this phase, modular concepts reduce the number and complexity of crane lifts, further boosting productivity, increasing cost benefits, and promoting safety.

The implications extend beyond speed. Stick-framing was customizable and forgiving but labor-intensive and slows down the construction progress on site. However, it is better for sequencing and working around variabilities in the field. Panelization delivered intermediate gains with prefabricated layouts and fewer clashes on site. Modularization produced the largest savings on-site by shifting complexity off-site; however, it required tighter coordination at diaphragm joints, modified hold-downs, and close tolerances with the interconnecting pieces, and significant coordination work in design. The Modular Stair System (MSS) removed temporary stairs and provided a consistent enclosure strategy across nine stories, helping keep the schedule on track.

The present observations emphasize that the construction strategies enabled efficient installation while sustaining performance under severe seismic demands. Design standards do not explicitly address modular interfaces, diaphragm-edge blocking, or stair-to-diaphragm connections in multi-story CFS systems. Results from CFS10 indicate that while CFS modules demonstrated resilience and practicality, connection details still have room for improvement, warranting further research to advance modular interfaces and support future updates to design guides and codes.

PRACTICAL FINDINGS AND APPLICATION FOR CONSTRUCTION

The CFS10 test program resulted in several practical findings with direct application for construction, including the following:

- Clear differences in on-site labor across stick-framed, panelized, and modular installation were observed. Modularization was the fastest approach, requiring only 15% of the panelized man-hours and 9% of the stick-framed man-hours. The shorter on-site duration reduced congestion, crane use, weather exposure, and risk, which improved working conditions for the crew. However, it is notable that modular construction requires higher coordination compared with other construction methods, therefore full BIM integration was vital for its success.
- The design and installation of CFS modules advantageously served to facilitate lift of additional materials required for completion of construction within a given floor level, leading to an efficient use of crane effort due to the enclosed nature of the module.
- In this program, the modules required assembly on-site due to transportation limitations. While the efficiency of their assembly was improved by constructing them of panelized floors and walls, designing the project as modular in the early stages should consider transportation limitations (from shop to site), with the aim of avoiding these constraints and assuring factory quality from the beginning.
- Module-to-module interlocking was easier for the construction team when the crew had a positional reference, such as the hold-down plates, to guide the module during lifting and placement. It is important in module connection design to provide simple reference points that help the crew align the module as it is set.

- The self-supporting modular stair system often ran one floor above the active work level during construction. This layout improved access and eliminated the need for scaffolding.

As of this writing, the specimen has completed all testing phases and was fully deconstructed. An interesting aspect of this phase was during deconstruction, the modular units were removed intact while the panelized side had to be taken apart panel by panel, which underscored modular construction's advantages for speed, safety, and control in both assembly and deconstruction. Future publications will build upon data and observations from this effort, including the lead author's thesis (in progress at the time of writing), which aims to synthesize the design decisions, implementations, and their relation to practice as implemented within the landmark CFS10 building program.

ACKNOWLEDGMENTS

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