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## **The Stability of Resilient and Sustainable Structures**

Jerome F. Hajjar<sup>1</sup>

### **Abstract**

This paper is presented in honor of Lynn S. Beedle, a faculty member at Lehigh University and a pioneer in the field of structural steel design, structural stability, and international cooperation in structural engineering. Dr. Beedle fostered an era of unprecedented international cooperation in the years following World War II. He valued fundamental advances in the profession, leading a number of seminal projects related to structural steel behavior and design. Moreover, he was consistently interested in supporting and advancing the forefront of the field, to the point of founding a new professional society, the Council on Tall Buildings and Urban Habitat, that remains thriving to this day. In our current time of evolution within the structural engineering profession, Lynn Beedle provides a model for how to foster innovation, cooperation, and transformative advances. Structural engineering design has historically had a focus on addressing strength, stability, serviceability, constructability, aesthetics, and economy. These critical design objectives underpin our philosophical and technical approaches to structural design. However, a confluence of opportunities and national and international grand challenges are influencing current directions in the design of structures, particularly within urban regions as populations continue to expand and key resources become scarcer. This paper summarizes new developments to create resilient and sustainable structures, focusing on steel and composite steel/concrete structures. Research on resilience of structures highlights the development of structural systems that are able to be returned to use quickly after extreme events, thus having the potential to dramatically extend the life of the structure as well as facilitate speedy and safe recovery within a community. Sustainable structural design, in turn, highlights strategies for developing new structural systems that greatly decrease the amount of energy, material waste, pollution, and greenhouse gas emissions in construction and use of buildings and other structures. To ensure the long-term stability of these new approaches within the built environment, embedding resilience and sustainability in structural design will require more than technical innovations: it will require a shift in mindset by structural engineers and those affiliated with the construction and use of structures. This paper is put forward in the spirit of Lynn Beedle, whereby international cooperation, forged through new relations and potentially through new organizational structures, will be important for fostering a comprehensive approach to achieving sustainable and resilient design across our infrastructure. By providing examples from recent research to address resilience and sustainability in structural systems, this work offers insights into how engineering innovations can be used to create a new generation of solutions for structural design.

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<sup>1</sup> CDM Smith Professor and Department Chair, Northeastern University, [jf.hajjar@northeastern.edu](mailto:jf.hajjar@northeastern.edu)

## 1. Introduction

The Northridge, California Earthquake of January 17, 1994, caused damage to steel structures through fractures in the steel connection regions. A comprehensive research program was executed in the years following through the SAC Joint Venture (Hamburger et al. 2000) and other national efforts, eventually underpinning a complete revision in 2010 of AISC 341 *Seismic Provisions for Structural Steel Buildings* (AISC 2010). Numerous successful approaches for connection design were developed to mitigate the risk of fracture in the connection region (Roeder 2000), leading in part to the development in 2005 of AISC 358 *Prequalified Connections for Intermediate and Special Steel Moment Frames for Seismic Applications* (AISC 2005), which lays out the design strategy for nearly a dozen different types of steel connections in seismic zones.

Most of these approaches absorb the energy from an earthquake through yielding in the steel girders or connection components, typically at a distance away from the column face sufficient to mitigate the risk of fracture initiation at the girder-to-column interface. For example, as part of these efforts, research was conducted on the impact of composite floors and column stiffening on the fractures that occurred in the steel connections (Leon et al. 1998; Hajjar et al. 1998; Lee et al. 2005a, 2005b), emphasizing the embedded reliance on plasticity in the connection region to dissipate the energy from the earthquake. While these approaches are effective in ensuring safe structural systems, most of them are not conducive to fostering structural resilience through facilitating speedy occupancy after a significant structural event. More broadly, current seismic force resisting systems, including moment frames, braced frames, and wall systems, focus damage during an earthquake into the primary structural components, including the girders, braces, the bases of the walls, and the connection regions in such a way that new, well-designed buildings may be subjected to significant structural damage throughout much of the seismic force resisting system after a major or moderate seismic event, resulting in damage that is extensive and potentially expensive or extremely difficult to repair. Resilient structural systems have been developed over the last one to two decades that provide the opportunity to shift this approach towards using articulated, replaceable energy-dissipating components, made of standard structural materials and employed in configurations that are readily constructable. These systems have the potential of limiting the cost and scope of repair after a significant event.

In addition, there is increasing opportunity to develop strategies to address sustainability in structural systems. Data from the U.S. Department of Energy indicates that construction and use of commercial and residential buildings in the United States accounts for approximately 40% of U.S. energy consumption, while the industrial sector and the transportation sector each accounted for an additional 30% (EIA 2015). The energy consumed to manufacture building materials and construct buildings is included within the industrial sector metric. This figure related to energy use is compounded by the waste currently associated with industry. In addition to consuming large quantities of natural resources and emitting a variety of pollutants, including greenhouse gases, construction and demolition of buildings produce vast quantities of material waste. According to a study prepared for the U.S. Environmental Protection Agency (EPA 2009), building-related construction and demolition waste amounted to approximately two-thirds of all non-industrial waste in the U.S. Demolition constitutes nearly half of this amount, with renovation and new construction constituting the remainder. A United Nations Environment Programme report notes that 40-50% of total material flows worldwide are into building materials (UNEP 2007).

Hot-rolled structural steel used in the construction of steel building structures and infrastructure components currently is produced in the U.S. from nearly 100% recycled materials (AISC 2024). A variety of sustainable concrete mixes are also being developed worldwide (Gregory et al. 2021). However, even the use of recycled materials still consumes significant energy, currently often derived from non-renewable fossil fuels. Achieving comprehensive sustainability in the built environment requires significant reduction in the use of most non-renewable resources, both for construction materials and for energy consumption. In addition, through the adoption of resilient design approaches that facilitate speedy repair and reoccupancy, structures can potentially be designed to have much longer lifespans than is common currently.

As such, this work proposes several strategies to address sustainability and resilience in structural systems:

- ***Modular Steel Construction:*** There are significant opportunities to address both sustainability and resilience through the use of modular steel construction. Fabrication of structural components in the shop is efficient and potentially reduces waste, and an increasing number of contractors are seeing benefits in modular construction to limit labor in the field. Modular steel buildings are increasingly popular in the building industry because of the potential benefits they provide: shorter construction times, lowers costs, and increased quality controls (Lawson et al. 2012). In addition, modular systems can provide logical connection points at which articulated energy-dissipation may occur as replaceable components.
- ***Spine-based structural systems:*** All systems in the AISC *Seismic Provisions* (AISC 2022) rely fundamentally on systems that have story-based modes of failure, and thus they focus on story-based capacity design strategies that try to ensure that each story is sufficiently strong, but with little direct accounting for the overall global behavior of the structural system. Thus, the failure mode of the structure may be controlled by localized damage in one story. Alternatively, spine-based systems (Eatherton et al. 2014) rely on a stiff elastic spine that minimizes the risk of a story-based failure mode. These systems offer direct opportunity to have the energy dissipation focused in articulated replaceable components while reducing the risk of damage in the remainder of the structure.
- ***Articulated Replaceable Energy-dissipating “Fuses”:*** Energy-dissipating “fuses” enable ductile response to be focused in specific areas of the structure. Examples of existing replaceable energy-dissipating fuses include the beam-end damper from Nippon Steel Engineering (Kishiki et al. 2004); ADAS hysteretic dampers (Xia 1990), buckling-restrained braces (BRBs) (Takeuchi et al. 2010), and a variety of other manufactured devices. Eatherton et al. (2014), Hashemi et al. (2010), Ricles et al. (2010), and Mar (2010) and others have investigated allowing the structural system to rock in a controlled fashion so as to use this motion to engage the energy dissipating components.
- ***Self-centering of seismic load resisting system:*** After an earthquake or other extreme event, the likelihood of being able to reoccupy and reuse a structure is enhanced significantly through being able to self-center the structure, particularly if the intent is to replace the energy-dissipating components of the system. A variety of self-centering configurations have been explored recently, including self-centering braces (Christopoulos et al. 2008), steel plate shear walls (Clayton et al. 2015), and steel braced frames (Eatherton et al. 2014). Taken together, articulated fuse-based, rocking and self-centering structures offer a

transformative alternative to traditional systems, as these structural systems provide a key step towards designing more resilient structures that are both safe and reusable after a seismic event.

- ***Design for Deconstruction:*** Modular construction also facilitates *Design for Deconstruction (DfD)* (Kestner et al. 2010), an emerging design strategy to facilitate future reuse of materials. A key component of reducing the impacts of new construction is to utilize materials that have been salvaged from existing buildings that are no longer needed [see for example 270 Park Avenue in New York City (Depaola and Orlando 2024)]. In this approach, all building materials are selected and assembled in a manner that simplifies their future extraction and reuse. Modular construction offers particular advantages for Design for Deconstruction because the structure may be disassembled into modules for reuse in future structures. This offers the potential for creating whole new industries and supply chains aligned with the steel industry. Through using articulated structural components that are replaceable to dissipate energy in the lateral system, it is feasible to design systems in which most or all of the components may be reused in future structures even for structures subjected to moderate or extreme events, thus ensuring both sustainability and resilience in these designs.

Structural steel framing systems are particularly conducive to deconstruction at the end of the service life of a structure. As we move towards a sustainable construction industry, there are clear opportunities to develop modular steel structural components that are reusable. Steel lateral resistance systems like the moment-resisting frames produced by ConXtech (Renz 2005) provide an early indication of a potential new paradigm for sustainable steel construction. Steel structures also provide a significant opportunity for much richer optimization of materials and construction to minimize carbon footprint and use of resources.

The principles of *DfD* are closely associated with and lead to increased adaptability of a structure. Many buildings are removed from sites due to redevelopment. As such, *DfD* can also be an appropriate strategy to minimize obsolescence and environmental impacts through renovation and reuse. *DfD* requires flexibility in design and buildings that are designed and constructed in layers according to the service life of layer components. Components with a long service life should be designed to be adaptable, durable, and flexible so they can adapt to changing requirements. Those with shorter lifespans, such as replaceable fuses, may be designed to allow upgrading, repair, reuse, and replacement. These systems could be layered so that the most-replaced components form the most-accessible layers.

Material and connection choices are another key component of *DfD*. Materials should be of high quality, optimized to minimize energy consumption, carbon footprint, or related sustainability metrics, and capable of retaining their mechanistic and other properties over time to enable reuse. It will be important to be able to trace the provenance of materials and document any possible extreme events that may have damaged the material during the life of the structure. Connections should be readily deconstructable and accessible both visually and physically. Chemical and welded connections between modules (rather than within modules) would typically be minimized or avoided since with these types of connections it is difficult to separate constituting materials for reuse or recycling. In recent

years, clamping technologies have been developed for use with hot-rolled steel structures. These technologies provide exciting opportunities for *DfD*.

The combination of strategies such as these provide the basis for addressing sustainability and resilience. This paper highlights several structural systems that address sustainability and resilience for steel and composite steel/concrete structures.

## 2. Seismic Resilience Using Articulated Energy-Dissipating “Fuses”

Seismic design of spine-based structural systems with articulated energy-dissipating fuses and self-centering tendons present unique advantages over conventional systems. Self-centering fuse

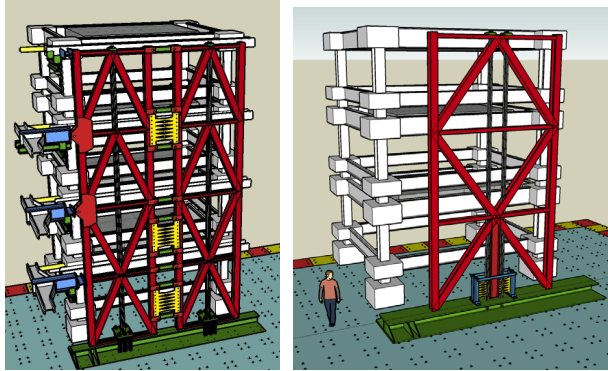


Figure 1: Configurations for articulated energy-dissipating fuses in steel building structures: a) fuses between braced frames; b) fuse at base of frame.

systems are comprised of a combination of two parallel sub-systems, one of which is characterized by bilinear nonlinear recoverable elastic response from the self-centering devices (with a stiff response until uplift, followed by a shallow load-deformation response from the recoverable post-tensioning elongation), and the second by a cyclic hysteretic response from the material nonlinearity within the fuses (Fig. 1). When properly proportioned, the two work together to provide the resulting flag-shaped hysteretic response, such as seen in Fig. 2c (Deierlein et al. 2011). In addition to design parameters that govern the overall system response, design methodologies for such

systems must address the system capacity design requirements.

In this work, replaceable steel shear plates were used as fuses configured between two rocking frames as shown in Figs 1 and 2 (Deierlein et al. 2011; Eatherton et al. 2014a, 2014b). Post-tensioning provides self-centering force as the structural damage is concentrated in the Grade A36 steel fuse plates cut into a ‘butterfly’ pattern (Fig. 2a).

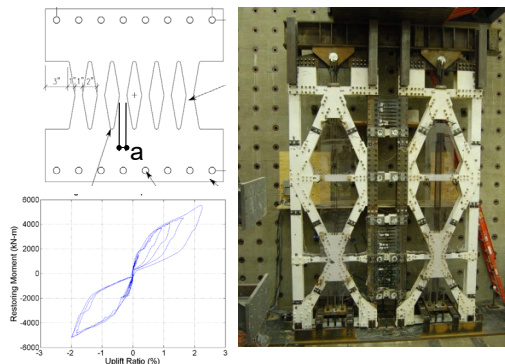


Figure 2. a) Steel butterfly fuse; b) system rocked at 4% drift in quasi-static cyclic test of system; c) load-deformation of shake-table test of system.

The research showed that the ‘butterfly’ pattern gave excellent cyclic hysteretic response (Deierlein et al. 2011). The butterfly fuse, readily fabricated using water cutting in a standard steel fabrication shop, was arrived at after a computational and experimental investigation of the stress patterns in the plate, including a series of tests of the fuses of different thicknesses and cutout dimensions subjected to cyclic shear stress. The system performed well overall in a series of large-scale tests, including quasi-static, hybrid simulation, and shake-table experiments. In the shake table tests of three-story structures at two-thirds scale, dynamic effects were shown not to amplify forces in the rocking system unduly (Deierlein et al. 2011). Ongoing work continues to investigate the adaptation of capacity design approaches to structural systems

like this, and to ensure integrity of the system for higher mode effects. For low-rise structures, by far the most common type of steel structure, these readily constructable systems provide examples of resilient design that may be adopted broadly in steel design.

### 3. Hurricane Resilience using Replaceable Dampers

High wind speeds during hurricanes can severely damage electrical transmission networks. Since the locations of many steel lattice transmission towers may be difficult to access, the failure of these towers often hinders the restoration process (Reed et al. 2010). Consequently, severe electric outages can be caused during and after hurricanes. For example, immediately after landfall of Hurricane Rita in 2005, more than 500,000 customers lost their power in the state of Louisiana, while in Texas, more than 1,500,000 customers were heavily impacted.

The resilience of electrical transmission systems subjected to hurricane loading provides an example of a crucial lifeline system in which rapid recovery in disaster areas is essential. This research conducted robust and comprehensive probabilistic hurricane collapse safety assessments of electrical transmission structures, which provides the foundations for developing approaches for resilient design of structures subjected to hurricanes. In this work, simulation methods were used to predict the collapse behavior of electrical transmission towers and reliability methods were used for characterizing the influence of hazard uncertainties on the overall hurricane response of electrical transmission towers. This work represents some of the first fully nonlinear dynamic time history analyses conducted on transmission line towers for the full duration of a hurricane (Du and Hajjar 2022).

In this work, a methodology was developed to select representative hurricanes at specific locations and establish the complete bi-directional loading history of the wind forces at different heights along the structure. A 10,000-year synthetic hurricane catalog developed by Liu (2014) for the Atlantic basin was used to collect hurricane mean wind speed and direction records. The hurricane wind fields were calculated using the model proposed by Georgiou (1986) with the data provided by Liu (2014). An example of the collected 10-minute hurricane mean wind speed and direction records at a location of interest in the Northeastern United States is shown in Fig. 3b with the corresponding hurricane track in Fig. 3a.

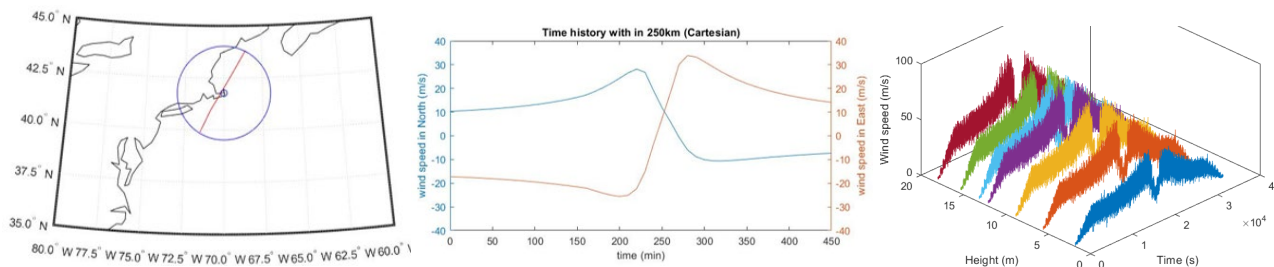


Figure 3: Sample hurricane: a) typical track; b) wind speed in North and East directions over hurricane duration; c) simulated hurricane wind field at different heights of a structure.

The hurricanes being used in this work have 10-minute mean wind speeds that are recorded every 10 minutes (Du et al. 2023). As such, the selected hurricane wind records are time series that set a new value of the mean wind speed every 10 minutes at a height of 10 meters on the structure. For structural analysis, a logarithmic law is adopted to generate mean wind speed values at loading points of various heights along the height of the structure, assuming an open terrain. In addition, fluctuating wind time histories are used within the 10-minute time step at a specific value of mean

wind speed. The fluctuating wind speeds were generated using the Kaimal spectrum (Kaimal 1972). As an example, Fig. 3c presents the simulated wind speed time series combining both the mean and fluctuating wind speeds. These are the values of wind speeds without resolving to North and East. The directions of wind speeds are not shown in Fig. 3c but were included in the analyses. In addition, the first hour and the last hour with 10-minute intervals at a constant mean were added to the wind speed histories as the ramp-up and ramp-down to avoid impulse effects.

A prototype transmission tower made of steel angles with a height of 18 m is shown in Fig. 4a (Du and Hajjar 2022). For geometric and material nonlinear structural analysis, the tower was analyzed using a beam element developed Du and Hajjar (2021a, 2021b) and implemented in OpenSees (McKenna et al. 2010). Both displacement-based and mixed beam elements were developed to simulate the nonlinear behavior of asymmetric sections such as steel angle members used in transmission towers. Fiber-based cross section formulations were used to address the inelastic behavior in both the displacement-based element and the mixed element. While the mixed element

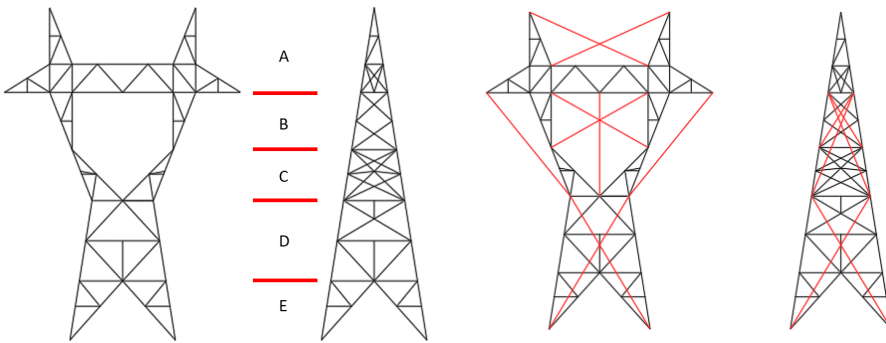


Figure 4: a) Prototype transmission tower; b) transmission tower with dampers (in red).

is more computationally intensive than the displacement-based element due to the complexity of its formulation, it can better model nonlinear curvature within an element. Consequently, for cases in which the nonlinear distribution of curvature is significant, such as in concentrated

plastic hinge regions, the mixed element is more accurate. As such, fewer mixed elements are needed to obtain similar results as compared to the displacement-based element.

For this beam formulation, to capture the axial-flexural-torsional interaction behavior of slender members with asymmetric sections, such as steel angles, the Green-Lagrange strain is used within a total Lagrangian approach in the basic system of the corotational transformation method. The 6 degree-of-freedom (DOF) element is formulated in the basic system at each time step. This is then transformed to the 12-DOF global system through the use of a corotational transformation matrix. The corotational transformation matrix is time dependent since the basic system translates and rotates continuously with the moving element chord. The deformations are captured in the basic system, while the rigid body motions are considered using the transformation matrix relating the global and basic coordinate systems.

Using the calculated wind forces from a suite of scaled hurricane wind records (Du et al. 2023), incremental dynamic analysis (IDA) was run on a transmission tower in OpenSees to predict the collapse capacity of the tower (Du and Hajjar 2022). Incremental dynamic analysis, similar to what is used in earthquake engineering (Vamvatsikos and Cornell 2002), was used to establish the onset of collapse based on maximum displacement at the top of the tower. Collapse was defined when the slope of the IDA curve reaches 20% of the elastic slope. The obtained incremental dynamic analysis curves are shown in Fig. 5a along with the specified collapse capacities. This type of data may then be used to construct a fragility curve that tracks the likelihood of collapse for a given

magnitude of wind speed during a hurricane, such as shown in Fig. 5b. These types of simulations are important for enabling predictions of collapse within a region. In addition, the use of artificial intelligence has the potential to greatly speed up the extensive processing time required to conduct the creation of fragility curves. For example, work by Bond et al. (2023, 2024) is developing training procedures to produce nonlinear dynamic results of structures subjected to earthquakes through physics-informed machine learning.

A variety of approaches have been explored for enhancing the resilience of transmission line towers. Chen et al. (2014), Lan et al. (2020), Roy and Kundu (2021) have explored the use of viscous dampers, acting essentially as fuse systems to absorb much of the energy from the hurricane. Lan et al. (2020) suggested an arrangement of dampers such as are shown in Fig. 4b.

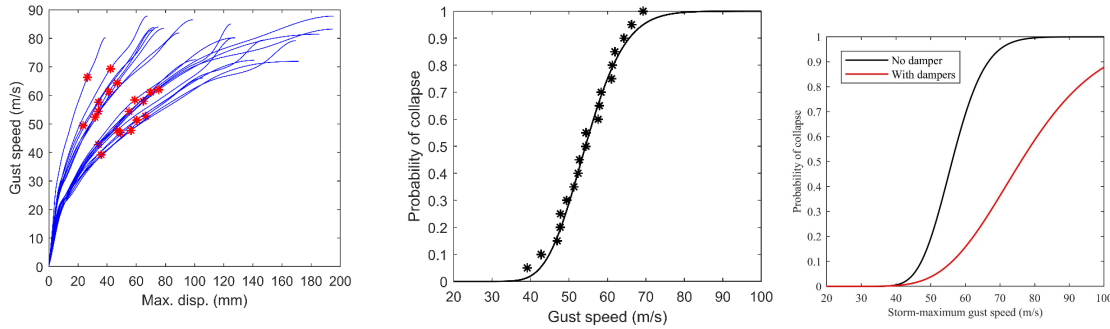


Figure 5: a) IDA for hurricane loading with predicted collapse points (stars); b) collapse fragility curve for the transmission tower due to hurricanes along with the simulation data (stars); c) comparison of fragility curves of towers with and without dampers.

To explore the impact of replaceable damper “fuses” on transmission towers, the viscous damper material in OpenSees was used to model the nonlinear behavior of viscous dampers (Akcelyan et al. 2018), and a comparable IDA analysis was conducted for the selected hurricanes (Du and Hajjar 2022). The resulting fragility curve is shown in Fig. 5c as compared to the fragility curve without the dampers to show the significantly enhanced collapse capacity that may be obtained. This type of exposed steel structure is also conducive to use of recently developed autonomous robotic inspection strategies to ascertain damage automatically after extreme events (e.g., Yan and Hajjar 2021; Yan et al. 2021; Yan and Hajjar 2022).

#### 4. Sustainable Structural Systems Using Design for Deconstruction for Composite Steel/Concrete Floor Diaphragm Systems

This work highlights the potential of deconstructable systems to be used to enhance the sustainability of steel structures by reusing rather than scrapping or recycling the vast majority of materials used within the structural system. In this work, new approaches for Design for Deconstruction have been developed to address composite floor framing systems, by far the most ubiquitous type of structural steel framing for commercial and institutional buildings (Eckelman et al. 2018; Wang et al. 2019, 2020). A schematic of a deconstructable composite beam investigated in this work is illustrated in Fig. 6a, which was first put forward by Webster et al. (2007). Precast concrete floor planks are attached to steel beams and girders with clamps (Lindapter 2012). The clamp connections are designed to provide composite action in the system. Channels that are cast into the planks to allow beams of any flange width to be attached at any



location. The strength and ductility of the connectors were documented in monotonic and cyclic pushout tests that represent the transfer of shear from the planks to the steel beams (Fig. 6b).

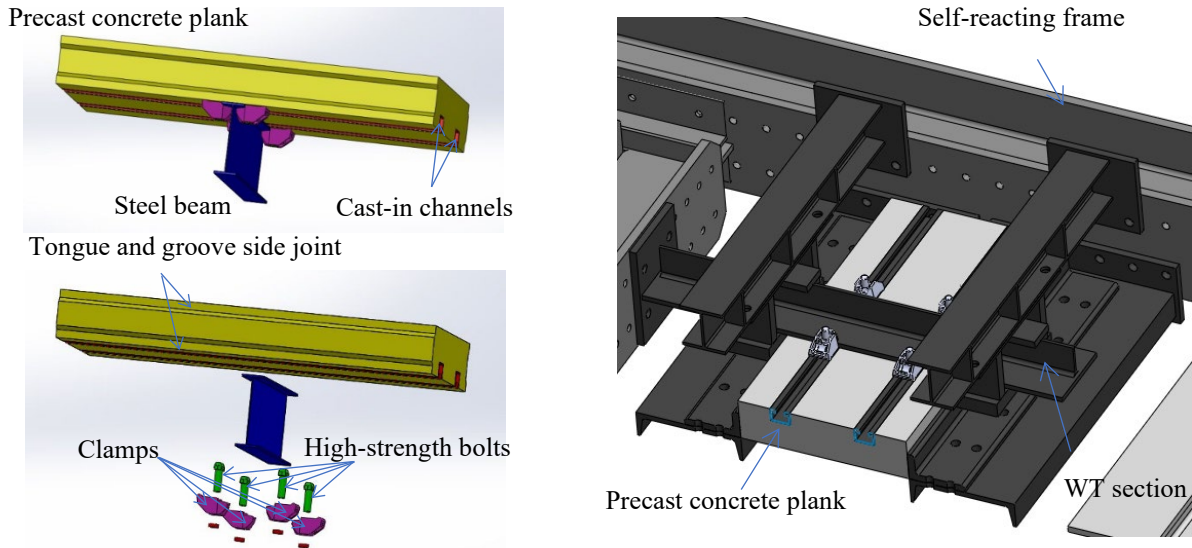


Figure 6: Deconstructable composite beam a) prototype system and b) test setup.

Typical load-slip curves for the clamps utilized in composite flooring systems are depicted in Fig. 7 for a monotonic test and the corresponding cyclic test with two cast-in channels and four clamps attaching the WT (representing the top flange of a beam) to the plank using 1 in. bolts. In the monotonic test, the average peak load for one clamp connector was 22.1 kips, comparable to 21.5 kips for a  $\frac{3}{4}$ " shear stud embedded in 4 ksi solid concrete slab, and comparable to the strength of a  $\frac{7}{8}$ " A325 bolt. The connectors retained approximately 80% of the peak capacity even at a slip of  $\pm 2$  in. Compared to the monotonic test results, the peak load was initially reduced modestly in the cyclic test due to the lowering of the coefficient of friction, but the strength then stabilized and large slips could be attained with little loss in the strength that may be used for reliable design. The corresponding beam test setup and load-deflection results are shown in Fig. 8, exhibiting excellent behavior. Four different beams were tested, each 30 feet long, simply supported, with composite action ranging from approximately 45% to fully composite action. The test results shown are for a W14x38 beam (Grade A992 steel) with fifteen precast concrete planks, each 8' long x 2' wide x 8" thick with a 5 ksi nominal concrete strength. The clamps were designed to provide 45% composite action using measured properties with two clamps being used per plank. All beams achieved the AISC composite beam strength and exhibited excellent ductility.

The benefits of *DfD* become apparent when conducting a life cycle assessment (Eckelman et al. 2018). Figure 9 shows typical results of a life cycle assessment of a prototype structure that consists of a three-story building with 20'x20' bays and a 6" nominal slab thickness, comparing a traditional structure with a concrete slab on metal deck to a structure using Design for Deconstruction, ranging from 0 to 3 reuses to show the dramatic reductions in key metrics.

Design for Deconstruction has the potential to create whole new industries, with reusable steel and composite components stockpiled in supply centers. Future work will need to continue to develop approaches for documenting the provenance of materials, the historical loading on a structure to ensure material integrity, and appropriate testing mechanisms to document materials strengths of reusable components.

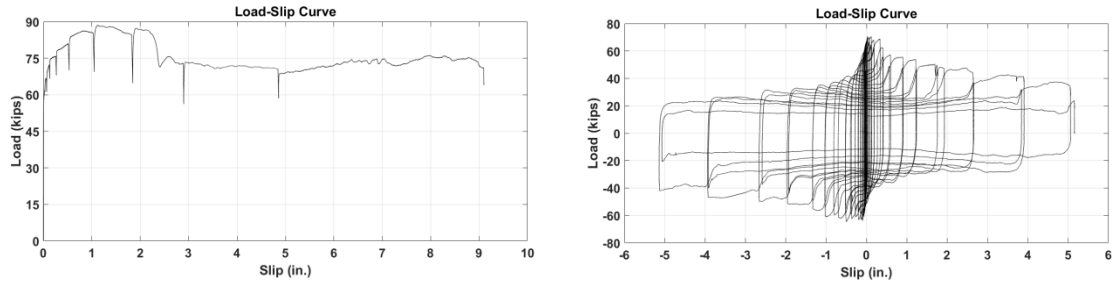


Figure 7: Load-slip curves for clamp pushout tests specimens under a) monotonic load; b) cyclic load.



Figure 8: Deconstructable composite beam test a) test setup; b) photo of damaged specimen; c) typical test results.

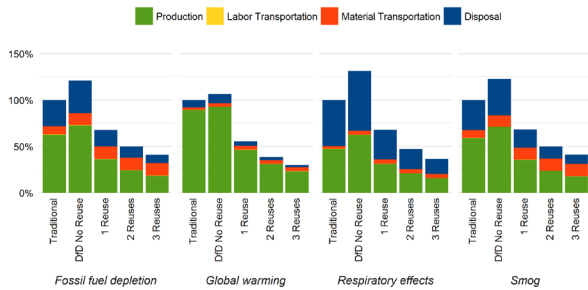


Figure 9: Comparison across life cycle stages and impact categories of a prototype structure using *DfD*.

In recent years, research as part of the Steel Diaphragm Innovation Initiative has been conducted on the three-dimensional behavior of composite concrete-filled steel deck floor diaphragms in steel building structures subjected to earthquakes (Briggs et al. 2022; Briggs and Hajjar 2023; Padilla-Llano et al. 2022). A series of experiments were conducted on the cyclic behavior of floor diaphragms, culminating in a full-scale multi-bay experiment that documented the progression of damage in typical composite floor diaphragms with metal deck, as are commonly used in steel buildings worldwide.

Figure 10 shows a schematic of test setup and a plan view of the damage at the end of the test. The specimen used Grade A992 steel and lightweight concrete with a nominal strength of 4 ksi. The diaphragm was subjected to a quasi-static cyclic loading protocol (Briggs and Hajjar 2023). The diaphragm showed significant overstrength and excellent ability to withstand cyclic forces, transferring forces reliably to the seismic force resisting system. However, this type of construction is not conducive to reuse of components, nor does it focus the damage in readily repairable or replaceable components.

This research has led in turn to two ongoing projects to develop more sustainable and resilient floor diaphragm systems for steel frame structures. One project, entitled FastFloor, is exploring the development of an all-steel floor diaphragm system. Asymmetric modules consisting of two beams and a steel plate ranging from 3/8" to 1/2" thick are being developed to facilitate speedy

construction using steel material. This system also facilitates deconstruction and reuse of the components. As the steel industry shifts towards using 100% recycled material manufactured from 100% renewable energy, FastFloor provides an exciting alternative for sustainable construction.

A second project is exploring the seismic behavior of steel frame structures with cross-laminated

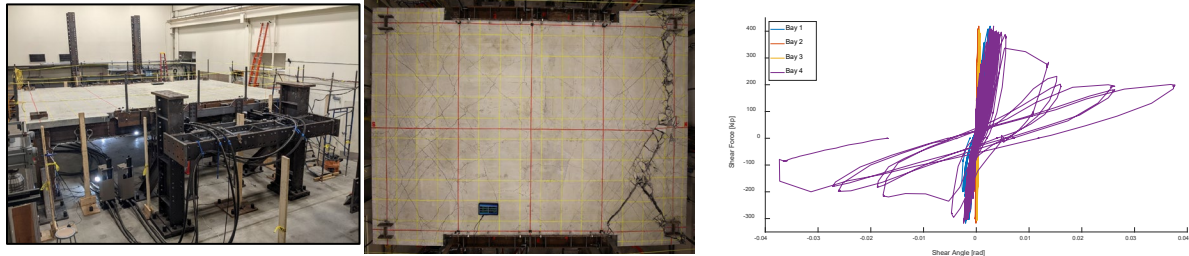


Figure 10: Composite concrete-filled steel deck diaphragm quasi-static cyclic test: a) test setup; b) photo of damaged specimen; c) shear force vs. shear angle results.

timber (CLT) floor diaphragms. The CLT material is intended to sequester carbon while simultaneously serving as the diaphragm system for the structure. The CLT planks will be developed and attached in a way to facilitate Design for Deconstruction. Energy dissipating fuses are being considered to enhance the resilience of this sustainable system. These types of diaphragm systems have the potential to transform steel construction to integrate resilient and sustainable design.

## 5. Conclusions

Structural engineers are critical to address resilience and sustainability in our communities. This paper summarizes several structural systems that have the potential to enhance the resilience and sustainability of steel and composite steel/concrete structural systems. Steel construction is particularly well suited for incorporating approaches such as modular construction, articulated energy-dissipating fuses, self-centering systems, and Design for Deconstruction. This work highlights the strength, stability, constructability, and structural integrity of several approaches for enhancing sustainability and resilience in steel and composite steel/concrete structures. Ongoing research is combining these key features to develop new systems that are more resilient and sustainable through the use of an all-steel structural system, and structures that use cross-laminated timber diaphragms within steel frame structures. Through systems like these, there is opportunity to facilitate resilience and sustainability becoming premier design objectives within the structural engineering profession, and, through that, to assure the stability of resilient and sustainable structures within the structural engineering design space.

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