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Earthquake resilient steel braced frames with controlled rocking and energy dissipating fuses

A new type of seismic resistant structural steel braced-frame system is introduced that employs controlled rocking, elastic post tensioning, and replaceable fuses to resist earthquake shaking with limited structural damage. Through the use of capacity design principles, inelastic energy dissipation is confined to replaceable fuses while the controlled rocking and elastic post tensioning provide self-centering action to eliminate residual drift. Quasi-static cyclic tests and dynamic shake table tests of large-scale specimens confirm that the system can sustain extreme earthquake ground shaking with story drift ratios up to 3 % without structural damage. Owing to the well-defined rocking mechanism, analysis and design of the system is straightforward. Work is ongoing to develop design criteria and guidelines to facilitate practical implementation of these system in building design and construction.

1 Introduction

Research and experience from past earthquakes suggest the need for buildings that are less vulnerable to damage and easier to repair after a major earthquake. Of particular concern are certain conventional systems, such as concentrically braced steel frame buildings, whose design may rely on more inelastic energy dissipation than the systems can provide. Our research aims to develop a new structural system that employs controlled frame rocking action and replaceable structural fuses to provide safe and cost effective resistance to earthquakes. The proposed system combines desirable aspects of conventional steel-braced framing with energy dissipating shear fuses that are mobilized through rocking action. Vertical post-tensioning is provided to increase over-turning resistance and enhance the self-centering characteristics of the system. This paper describes a collaborative project to develop the controlled rocking frame concept, including the planning, design, and testing of large-scale specimens at the NEES facility at the University of Illinois and on the E-Defense shaking table facility in Japan. Work is ongoing to develop design criteria and guidelines to facilitate use of these systems in practice. Further details of the quasi-static tests and the E-Defense shaking table test are provided in a companion paper by *Takeuchi* et al. [1] and technical reports by *Eatherton* et al. [2] and *Ma* et al. [3] and [4].

2 System design concepts

As illustrated in Fig. 1a, the proposed rocking frame system consists of a steel braced frame, which is designed to rock off its foundation, with overturning resistance provided by high-strength steel post-tensioning tendons and energy dissipating fuses. The lateral load resistance of the system (Fig. 1b) has a flag-shaped hysteretic loop that is characteristic of systems that self-center after large inelastic deformations. The overturning resistance is provided by a combination of the elastic restoring action provided by the prestressed steel tendons (Fig. 1c) and the energy dissipating fuses (Fig. 1d). The initial overturning resistance, $M_{OT,resistance}$, is a function of the initial prestress in the steel tendons and the yield strength of the fuse. During rocking, the steel tendons load and unload elastically, while the steel fuse yields and dissipates energy through hysteresis. The relative contribution of the post-tensioning tendons and fuse to the overturning resistance dictates the trade-off between the self-centering ability and energy dissipation in the system.

The self-centering rocking frame concepts can be employed in a variety of configurations to provide lateral resistance in steel-framed buildings. Shown in Fig. 2 are the two frame configurations, single-frame and dual-frame, investigated in this research. In both configurations, the steel braced frames are designed to remain essentially elastic during strong ground shaking, while the fuses yield and dissipate energy and the steel tendons stretch and provide an elastic restoring force. Since the steel braced frames are designed to remain elastic, apart from a few special details such as the rocking column bases and anchorage of the tendons and fuses, the steel frames employ fairly standard design, detailing and fabrication practices. The steel tendons can be located along the centerline of the frames (as shown in Fig. 2), or alternatively, can be located coincident with the columns of the braced frame. In the single-frame configuration, the fuses can be located either along the frame centerline or along the column line; whereas in the dual-frame configuration, the fuses are located be-

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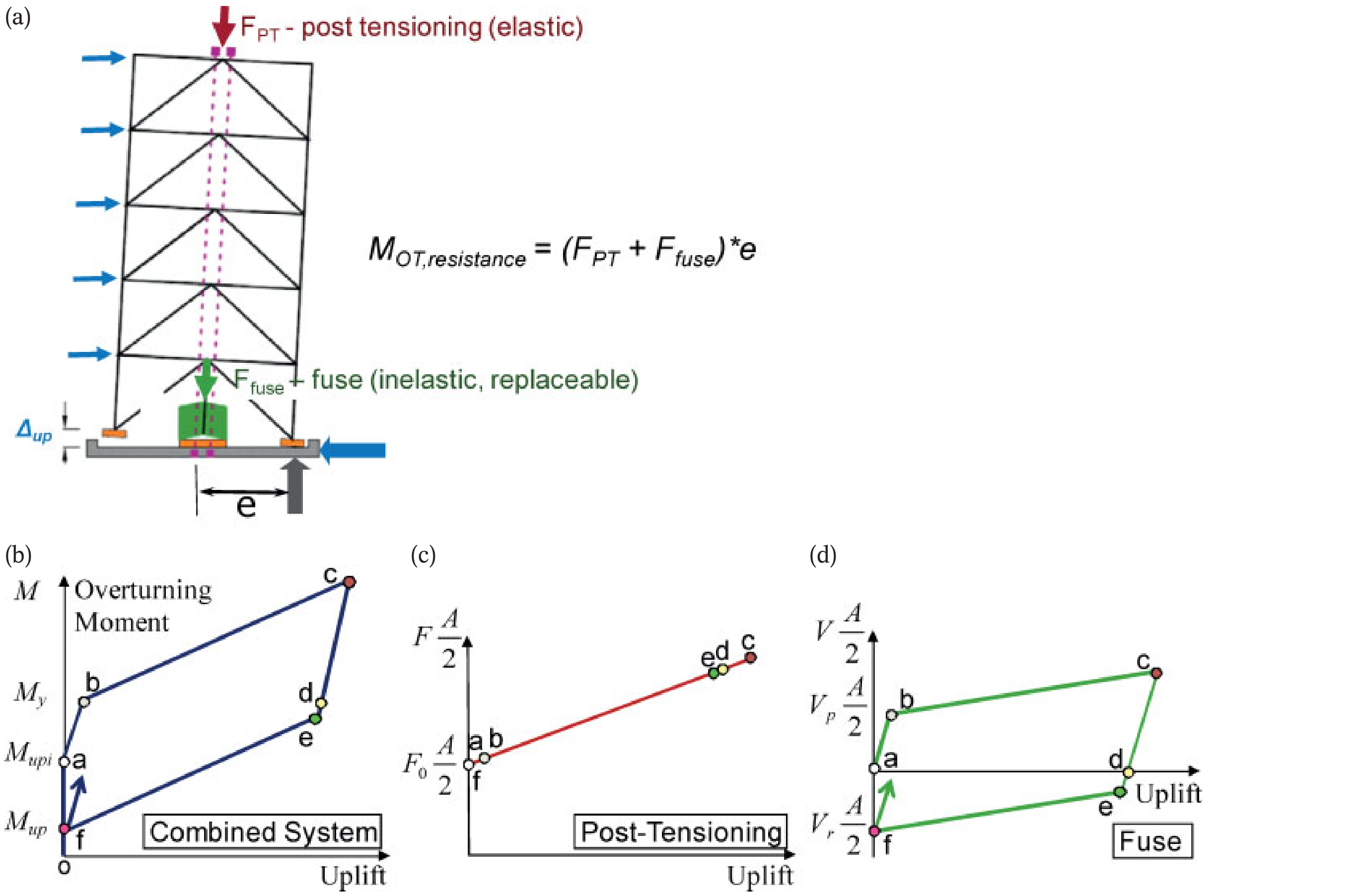

Fig. 1. Rocking frame; (a) schematic free-body diagram, (b) combined system response, (c) steel post-tensioning response, and (d) energy dissipating fuse response

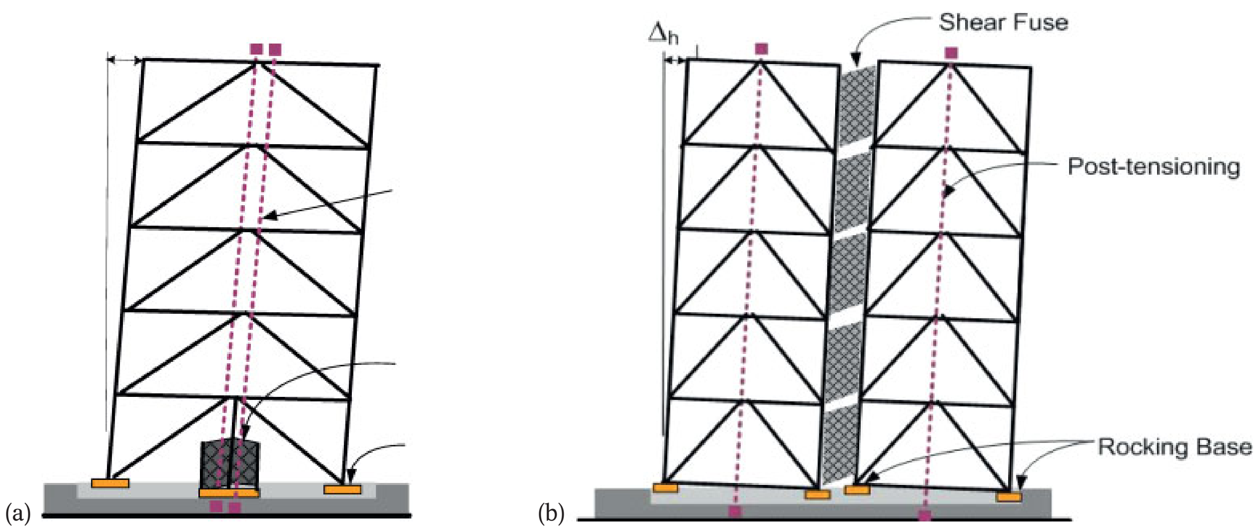

Fig. 2. Controlled rocking frame configurations; (a) single frame, (b) dual Frames

tween the two frames to maximize their energy dissipation. The fuses are designed and detailed as replaceable elements to facilitate repairs in the event that their energy dissipation capacity is exceeded in a large long-duration earthquake. Otherwise, the structural frames are designed to remain undamaged, even in very large earthquakes.

3 Replaceable butterfly fuses

The authors investigated several alternative fuse types and materials to provide energy dissipation for the rocking frame; and ultimately, two fuse types were employed. One type, the focus of a companion paper [1], consists of a conventional buckling-restrained brace, which is commercially produced by several companies in Japan and the United States. A second type, which was developed in this project, is a steel-plate butterfly-shaped fuse. As shown in Fig. 3, this fuse consists of a mild steel plate (e.g., ASTM A572 Gr. 50, Fy = 345 MPa) that is cut to create tapered butterfly-shaped links that distribute yielding and provide large inelastic ductility

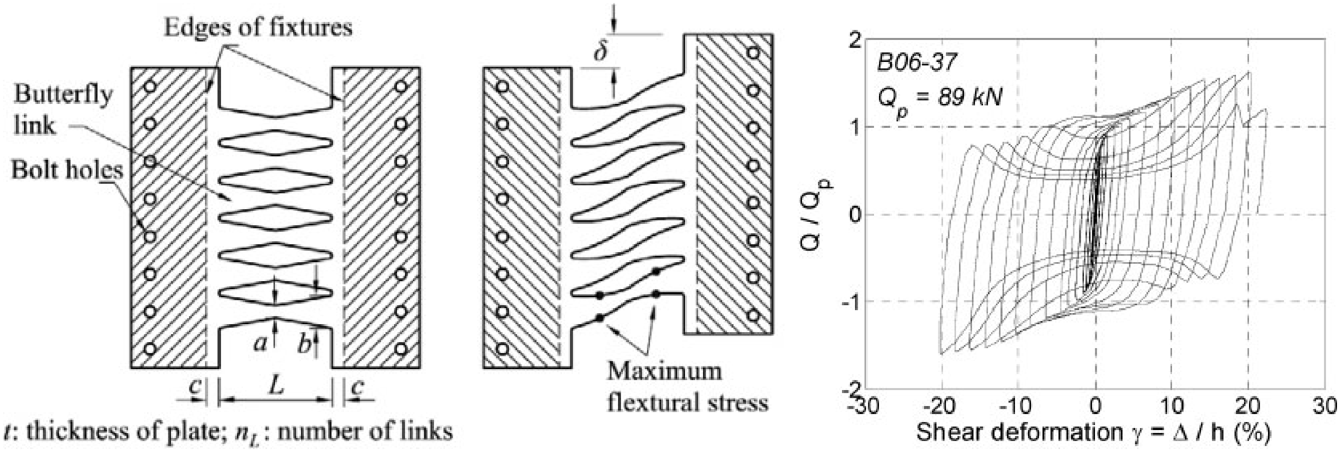

Fig. 3. Energy dissipating steel butterfly-shaped fuses

and energy dissipation capacity. The plates used in this study range in thickness from 8 to 25 mm and are fabricated with standard water-jet cutting to provide a smooth finish without introducing a heat affected zone that could adversely affect the material ductility.

As shown in the hysteretic plot of Fig. 3, under initial loading cycles the fuses exhibit stable yielding associated with in-plane flexure of the plate. Depending on the width/thickness (b/t) ratio, at some point the steel links experience out-of-plane torsional-flexural deformations that result in the pinched behaviour. Large deformation behaviour also creates tension stiffening in the links that preserves their peak strength. The degradation of the fuse at large deformations tends to improve the self-centering response of the rocking frames by reducing the force that the post-tensioning tendons must overcome to bring the frame back to plumb. Thus, an interesting design question for the fuse is the trade-off between strength and energy dissipation at low to moderate deformations versus degradation at large deformations. For further details on the fuse design, behaviour and testing, see [4].

4 Large-scale quasi-static tests

Half-scale dual and single frame configurations were tested under quasi-static cyclic and hybrid simulation loadings at the NEES laboratory of the University of Illinois (http://nees.uiuc.edu/). Shown in Fig. 4 is one of the nine tests that were conducted with varying configurations of fuses and relative amounts of fuse strength versus post-tensioning. The hysteresis plots in Fig. 4 were for a frame with thick non-degrading butterfly-shaped fuses where the fuse yield strength and initial post-tensioning force were set equal to each other.

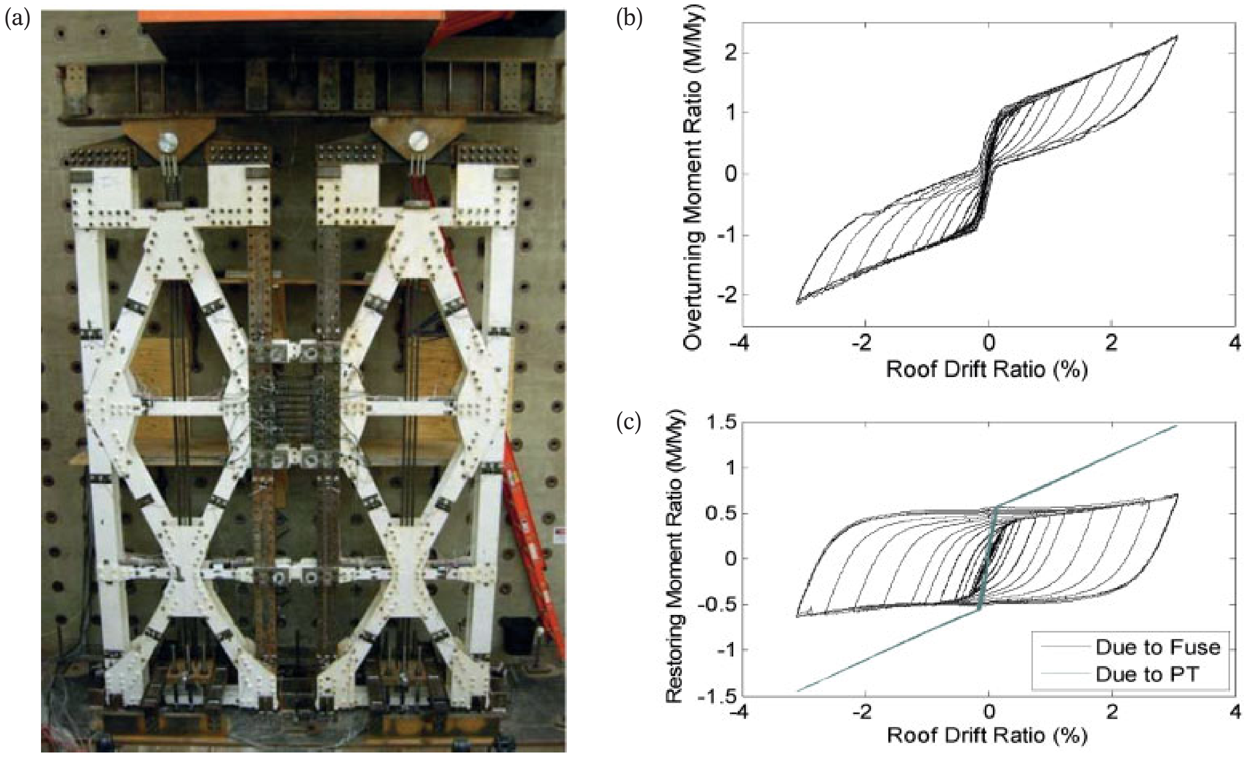

Fig. 4. Quasi-static cyclic testing of dual frame specimens; (a) test specimen, (b) overall hysteretic response, (c) components of hysteretic response

As shown, this combination of fuse strength and post-tensioning provided reliable self-centering behavior to drifts in excess of 0.03, which is beyond the drift expected in the so-called "maximum considered earthquake" (MCE) ground motion. The MCE is specified in US design codes to have a very low probability of exceedence, typically less than a 2 % probability of exceedence in 50 years. Further details of these tests and supporting analyses are reported by *Eatherton* et al. [2], but briefly, some of the key outcomes of the quasi-static tests are as follows:

- The tests confirm generally robust and predictable behaviour of the rocking frame, including the post-tensioning, fuse, and column base details.
- Trade-offs in performance are evaluated due to the relative overturning resistance provided by fuse yielding versus post-tensioning and the amount of fuse degradation.
- Hybrid simulations that include the dynamic response of the entire building system provide information on the balance of post-tensioning and fuse strength to achieve self-centering.
- The tests provide data on critical fracture limit states in the fuses and post-tensioning.

5 Large-scale shake table tests

Large-scale shaking table tests of the single frame configuration were conducted at the E-Defense facility in Japan (http://www.bosai.go.jp/hyogo/ehyogo/index.html) to provide a proof-of-concept and validate design and analysis techniques under dynamic earthquake shaking. As shown in Fig. 5, the rocking frame was positioned between two testbed units that supported the seismic mass that is equivalent to a three-story office building. Frames with three alternative fuse designs were tested under the JMA-Kobe and Canoga Park-Northridge ground motions that were scaled up to and beyond MCE level (2 % in 50 year exceedence) ground motion intensities for a high-seismic region. Shown in Fig. 6 is the roof drift and hysteretic response of the frame subjected to a ground motion roughly equivalent to the MCE level earthquake intensity. As shown, even with peak drift ratios in excess 0.02, the frame self-centered fully without any damage to the steel braced frame or the post-tensioning. Further, inelastic deformations in the fuse were well below its capacity, which was confirmed by subsequent shaking tests with satisfactory behaviour; and, accuracy of nonlinear analysis models was confirmed. Results of the tests with a buckling-restrained brace type fuse are reported by *Takeuchi* et al. [1], and more complete details of all tests are provided by *Ma* et al. [3].

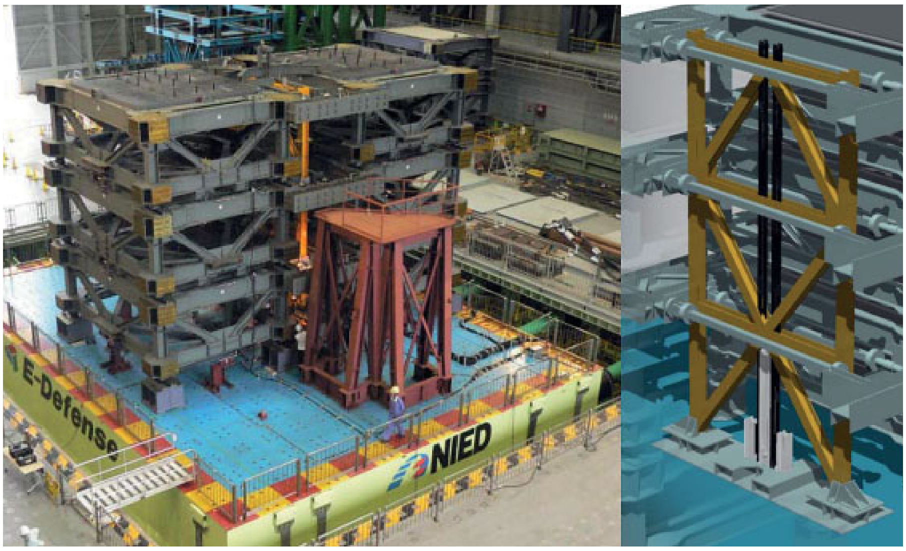

Fig. 5. E-Defense shaking table test of three-story frame specimen with seismic mass testbed simulator

Overall, the shake table tests confirmed the viability of the rocking frame concept and the expected behaviour of the system. Among the important specific conclusions from the tests:

- The system performed reliably to MCE-level drift ratios of 2.3 % to 2.9 % without any damage or loss in self-centering capability, i.e., without any residual drifts.
- The 7-wire post tensioning strands began to yield at drift ratios on the order of 3 % and maintained integrity (without fractures) at to drift ratios up to 4 %.
- The tests provided insights into the effect of alternative fuse designs with varying amounts of energy dissipation and degradation.
- The effect of rocking column impact forces was shown to not be a

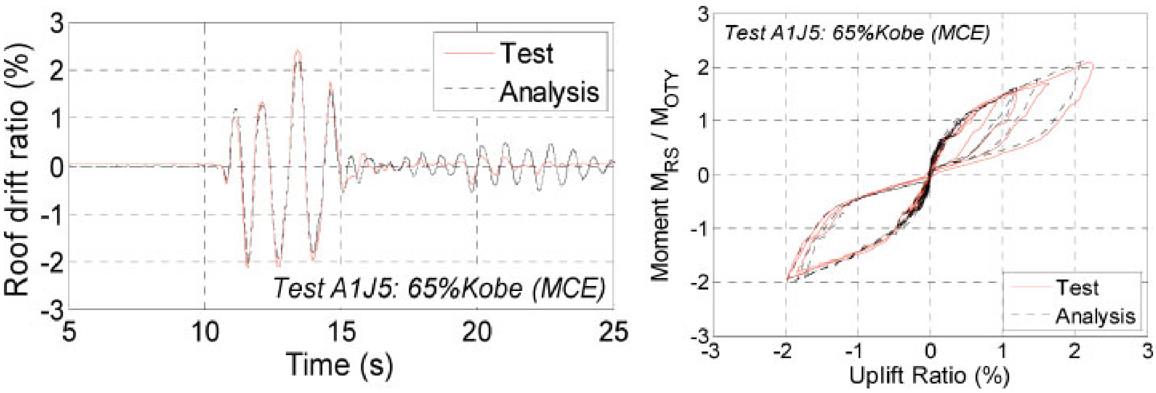

Fig. 6. Shaking table results: JMA Kobe motion scale to MCE intensity

controlling load case and not to have other negative effects on performance.
- Installation and replacement of post-tensioning strands and fuses provided insights into design and detailing to facilitate construction and post-earthquake repairs.

6 Performance-based design criteria

Data from the large-scale tests and analyses provide important information to validate analysis and design methods for the rocking frame systems. Referring to Fig. 7, there are generally two important limits in the design of rocking frames. The first limit corresponds to the point of initial uplift and fuse yielding of the system, which is primarily a function of the initial post tensioning (PT) force and the fuse yield strength. For the single-frame configuration with the PT and fuse in the center, the initial overturning resistance is given by the simple formula shown in Fig. 1a, and similar expressions can be developed for other configurations. The post-yield stiffness (beyond Θ_y in Fig. 7), depends on the frame configuration, the axial stiffness and stretch induced in the PT, and the strain hardening of the fuse. The second important limit state corresponds to the drift (uplift rotation) where the PT begins to yield followed by PT fracture and/or fuse fracture. These limit states would begin to severely impact both the self-centering capability and overall collapse safety of the frame.

The initial design concept for the rocking frames is to proportion to PT and fuses based on the following limit state checks: (a) the initial overturning resistance (M_y in Fig. 7) is proportioned to a similar level as other ductile seismic systems in US design standards (e.g., using a response modification factor of R = 8 under the design basis earthquake motions), and (b) drifts and uplift deformations under MCE level ground motions are limited to the lesser if 3 % drift or the uplift corresponding to PT yielding. Thus, these two limits are intended to provide comparable if not better performance than the most ductile seismic systems permitted in current

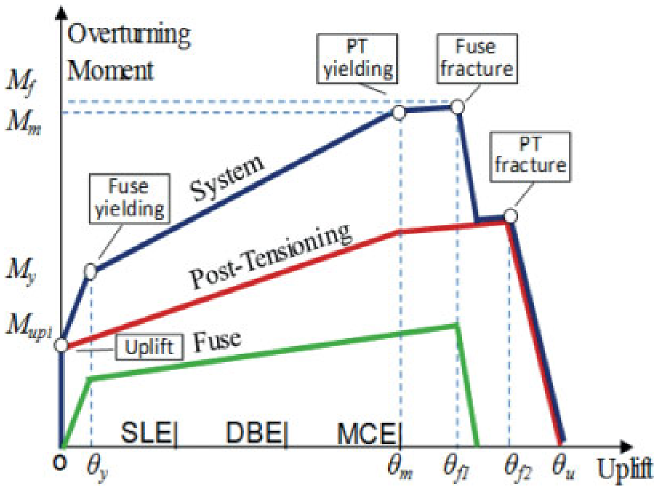

Fig. 7. Idealized static nonlinear response with critical limit states

building codes. Moreover, by tuning the PT and fuse strengths and proportioning the steel braced frame by capacity design principles, the system can be designed to prevent significant damage and residual drifts up to the MCE level ground motions. Further information on the proposed design recommendations is provided in [2] and [3]. The authors are continuing research to further develop and implement design requirements for earthquake engineering practice in the US and Japan.

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