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Sustainable Seismic Design of Steel Structures

Marzie Ansari Targhi MS[1*], Razie Ansari Targhi MS[2], Mark Grigorian MSc., DPhil [3]

[1]*Graduate student, Earthquake Engng. Dept, University of Science & Culture, Tehran, Iran*
[*] *marzieansary@gmail.com (Corresponding Author)*
[2] *Graduate student, Earthquake Engng. Dept., University of Science & Culture, Tehran, Iran, razieansary@gmail.com*
3Chief Struct. Eng., MGA Struct. Eng. Inc., 111 N. Jackson St. Glendale, CA 91206, markarjan@aol.com

ABSTRACT

Sustainability is one of the most underappreciated yet most influential traits of what is generally regarded as the laws of Nature and Engineering Mechanics that govern the workings of everything within the physical universe. Mixed Multiple Seismic Systems (MMSS) are ideally suited for Sustainable Seismic Design (SSD). MMSS are combinations of two or more different Earthquake Resisting Structures (ERS) that provide lateral support for gravity frameworks. Here, design means planning for both seismic resistance as well as Post-Earthquake Realignment and Repairs (PERR). Earthquakes are random, natural, and dynamic events, whereas PERR is a deliberate, manual, and static process. In SSD the practicality of PERR is as important as the relevance of the theoretical assumptions. In SSD the non-lateral resisting items are designed not to partake in seismic resistance, nor hinder the realignment process. Additionally, efforts are made to mitigate the P-delta effects that undermine the global strength of the system and oppose the recentering effort. The purpose of the current article is to identify and remedy design flaws and physical issues that prevent MMSS to achieve seismic sustainability as cost-effectively as possible. Two newly developed technologies, the ladder moment frame (LMF), and the Fail-Safe (FS) system as well as a capacity distribution rule together with six simple axioms have also been introduced.

Keywords: sustainability; multiple seismic systems; collapse prevention; reparability; fail-safe.

Notation:

C capacity

T tension

K global lateral stiffness

G shear modulus K_{EQ}

M^P plastic moment of beam

M_α^P plastic acting moment at distant a

M external/overturning moment

m_{EQ} equivalent mass

h_{EQ} equivalent height

$M_{E,0}$ preload moment

M_Y moment at first yield

ϕ_y drift ratio at first yield

ϕ_{res}, residual drift ratio

$\phi_{max,}$ maximum drift ratio

1. INTRODUCTION

Dual Seismic Systems (DSS), as particular cases of MMSS, are the most popular ERS worldwide. Codes define DSS as combinations of two conventional ERS, one of which may be highly ductile but poor in stiffness and the other much stiffer but lacking sufficient ductility. Research in SSD is perused in three different but related directions; (1) design methodologies, (2) structural configurations and supplementary devices, and (3) economics, health monitoring [1], and public awareness. In the first category, “Performance-Based Seismic Design” (PBSD) [2], “Direct-Displacement-Based seismic Design” (DDBD) [3], and recently “Performance Control” (PC) [4], offer more realistic basis for practical design of DSS and similar structures. The use of rocking walls and braced frames has significantly helped reduce seismic damage to conventional DSS, as reported, among others by [5-6-7-8-9]. It has also been shown by [10] that rigid rocking cores (RRCs) can enhance the seismic response of conventional ERSs and prevent plastic collapse while sustaining substantial seismic damage. The need for economic PERR has evolved into development of no damage, Fig. 1, and low damage/replaceable parts and joints, e.g. [11-12] as well as vibration dampers and energy dissipating devices, e.g. [13-14] for DSS configurations. However, despite the availability of highly informative literature on seismic sustainability e.g. [15-16-17-18-19], no complete DSS or MMSS archetype, including the gravity structure has been reported. Conventional gravity and ERSs sustain significant seismic damage and prevent residue-free realignment.

2. Analysis and Design Strategies

PERR is a manual operation, therefore it makes sense to resort to PC rather than PBSD for SSD. This allows structural actions such as suppression of higher modes of vibrations, imposition of sequences of failures of ERSs, prevention of soft-story failures, preclusion of physical collapse, enforcement of uniform drift, etc., to be treated as inherent properties rather than consequences of numerical studies. The difference between PBSD and PC [20], is that in the first instance design follows the performances of standard models with no regard to damage control or realignment, whereas in PC the same principles are used to control response in accordance with design objectives and a view to PERR and fail-safe operations. Fail-safe mechanisms are meant to reduce and/or prevent excessive displacements and to activate the post-yield reserve capacities of the structure for collapse prevention and PERR. Consequently, the development of SSD entails combinations of different methods of approach, including recognition and improvement of inadequate design concepts, use of adaptive technologies, and comparative functional studies. In SSD a structure is designed to either remain elastic or to be reparable after earthquakes. In SSD the engineer encounters opposing challenges, i.e., to design a system that can withstand the prescribed earthquake, and to be amenable to strength and stiffness reduction for PERR purposes. This is resolved by understanding the conditions that affect the capacity-stiffness-reparability relationships for different types of ERS.

3. Structural Attributes and Requirements

The capacity distribution rule is a notion that is well suited for SSD purposes. Fig.2(d) depicts the combined responses of groups 2(a) and 2(c) ERSs and can be regarded as a single degree of freedom representation of a potential seismically sustainable archetype. The black curve, ending in point **b** reflects the influence of the Pδ and gravity moments on the combined resistance of case 2(b), while the red curve, ending in point **c** on the same diagram, illustrates the contribution of the elastic arrangement on the global response of the system. Fig.2(d) provides valuable information for SSD. For instance, with K_{EQ} or K^*_{EQ} known, the base shear corresponding to ϕ_{max} can be estimated as,

$$V_{Base,\phi,max} = K^*_{EQ}\phi_{max}/h_{EQ} \tag{1}$$

Similarly, the fundamental period of vibrations, $T_{\phi,max}$ corresponding to ϕ_{max} can be related to K_{EQ} or K^*_{EQ} as,

$$K_{EQ}^{*}T_{\phi,max}^{2} = 4\pi^{2}m_{EQ} \tag{2}$$

The first yield moment of the system including the $P\delta$ and restoring effects can be expressed as,

$$M_Y = M_{E.0} + (K_E - K_{P\delta})\phi_Y + \phi_Y \sum_{i=1}^{n} K_i \tag{3}$$

The following observations were found to be useful for practical design of sustainable MMSS:

- The elastic arrangement and $P\delta$ effect act in opposition, both during the earthquake and PERR,
- Recentering, collapse prevention, and elimination of residual moments depend on the availability and magnitudes of the preloading, $M_{E,0}$, and stiffness, K_E, of the elastic arrangement,
- The $P\delta$ effect increases the residual distortions while the elastic arrangement tends to reduce it to zero,
- The $P\delta$ effect reduces the capacity of the structure while the elastic arrangement tends to increase it,
- The $P\delta$ effect elongates the fundamental period of the system while the elastic arrangement shortens it,
- The $P\delta$ effect reduces the equivalent stiffness of the system while the elastic arrangement increases it,
- The preload $M_{E,0}$ should be larger than the estimated residual moment ***oc*** for residue-free recentering,
- The total moment of resistance at ϕ_{max} should be greater than the estimated demand,
- If the last two requirements are satisfied, then perfect realignment can be expected, and
- If for any reason the total stiffness of group 2(a), the ductile ERS, becomes zero then recentering may be achieved by much smaller force following the new realignment path $(d - M_{E,0})$ instead of path ***dc***.

The SSD concept can be accomplished, within the frameworks of current codes of practice, provided that the basic principles of design-led analysis are followed. However, design-led analysis can be more effective if the following requirements for sustainable MMSS are clearly defined and incorporated as part of the design process:

1. Defining structural damage in terms of *tangible physical* phenomena such as yield drift ratio, maximum tolerable post-yield drift ratio, maximum tolerable residual distortions, and forces,
2. Preparing a *purpose-specific* health monitoring, maintenance, and inspection plan for PERR procedures,
3. Specifying protected zones for all critical joints, Fig. 1, and devices involved in PERR,
4. Provision of conditions for prevention of *local and global instabilities*, e.g., soft-story failure, etc.,
5. Prevention of damage to *essential elements* such as beams, columns, braces, and connections,
6. Providing the physical means for *collapse prevention*, e.g., stabilized RRCs, fail-safe devices, etc.,
7. Providing built-in devices and energy sources needed for realignment, e.g., stressing jacks, etc.,
8. Provision of minimum damage *repairable/replaceable* joints and fuses, e.g., RBS cover plates, etc.,
9. *Detailing* the gravity and nonstructural systems to *avoid* seismic resistance, and hinder the recentering effort,
10. Planning the *preferred sequences* of plastic failures of the ductile ERSs,
11. Details to be constructible by commonly available ways and means of construction,
12. Construction not to exceed the original construction cost,
13. PERR not to exceed a fraction of the cost of new construction,
14. Designing the PERR process using Global Stiffness Reduction (*GSR)* and Restoring Force Adjustment (RFA) technologies,
15. Planning for fail-safe operations as needed.

These requirements can be implemented by a combination of purpose-specific detailing and design-led analysis. The key formulae and concept schemes needed for preliminary design of sustainable MMSS are briefly presented in this paper. Two types of realignment are considered; “Forced” and “Assisted”. In the first instance, realignment is achieved using either stored energies within the system or an external source of the same magnitude, whereas in the latter case recentering is relied upon GSR and a combination of internal energies and RFA. Regardless of either option ϕ_{res} is the key parameter needed for decision making, thus,

$$\phi_{res} = \phi_{max} - \left\{ \left[\frac{(\sum_{i=1}^{r} K_i \phi_{Y,i}) - K_{P\delta}\phi_{max}}{(\sum_{i=1}^{r} K_i) - K_{P\delta}} \right] = \phi_Y \right\} \tag{4}$$

As a rule, recentering can take place if the restoring moment at $\phi = (\phi_{max} - 2\phi_y)$ is larger than the sum of all plastic and $P\delta$ moments acting on the system i.e.,

$$M_{E,0} + K_E(\phi_{max} - 2\phi_Y) > 2(M_Y - M_{E,0}) - [\sum_{i=1}^{n} M_i^P \quad + M_{E,0} + (K_E - K_{P\delta})\phi_{max}] \tag{5}$$

Given $M_{E,0}$, K_E of the core can be estimated as,

$$K_E > \left[\frac{2\phi_Y \sum_{i=1}^{n} K_i - \sum_{i=1}^{n} M_i^P - 2M_{E,0} + K_{P\delta}\phi_{max}}{2(\phi_{max} - \phi_Y)}\right] \tag{6}$$

The magnitude of the preload needed to reduce the residual moments to zero for forced realignment is given by,

$$M_{E,0} \geq M_{MMSS}^P \tag{7}$$

Then Eq. (6) should be reconsidered for perfect, residual moment-free realignment. The total capacity of the structure after exhausting the strengths of the ductile ERS can be expressed as,

$$[C_{Total} = M_{E,0} + (K_E - K_{P\delta})\phi_{max} + \sum_{i=1}^{n} M_i^P] > M_{Demand} \tag{8}$$

C_{Total} includes the preload $M_{E,0}$ and the quantity $(K_E - K_{P\delta})\phi_{max}$ needed for collapse prevention and PERR.

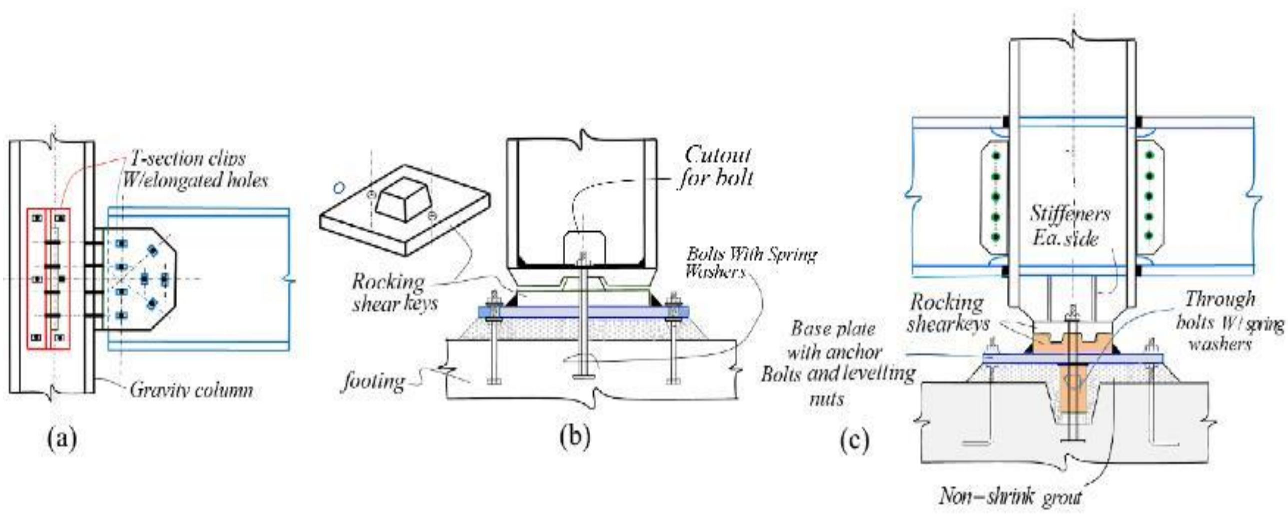

Fig. 1-(a) Proposed articulated beam column joint, (b) Proposed pinned base column support, (c). Proposed rocking base column support, partial fixity provided by the grade beams.

3.1. Forced Realignment

Point a Fig.2(b), marks the end of the seismic event and the extent of damage characterized by ϕres=2ϕ_Y. Point b indicates that a force equal to (-M_MMSS^P) would be needed to achieve PERR. The lower quadrant defines a possible forced recentering path from point a to b. Both the red (0-M_E0-m-d-c) and black (0-d-c) response plots of Fig.2(d) represent collapse

prevention and forced recentering. Note that ϕ_(res,) can be smaller than (ϕ_max- 〖2ϕ〗 _y), and that the residual moment after realignment could be as large as (-M_MMSS^P). Both conditions are undesirable but can be alleviated by including a sufficiently powerful energy restoring system, such as a stabilized RRC as part of the combination. Figs 2(b) and (d) exhibit total flag and pole heights (2M_MMSS^P) and M_(E,0) =0, respectively. Flag height less than (2M_MMSS^P) implies no meaningful PERR. Pole height less than (M_MMSS^P) means accumulation of residual stresses despite PERR. Assisted recentering addresses both issues by reducing the post-earthquake stiffness of the system to zero and selecting K_E≥K_Pδ.

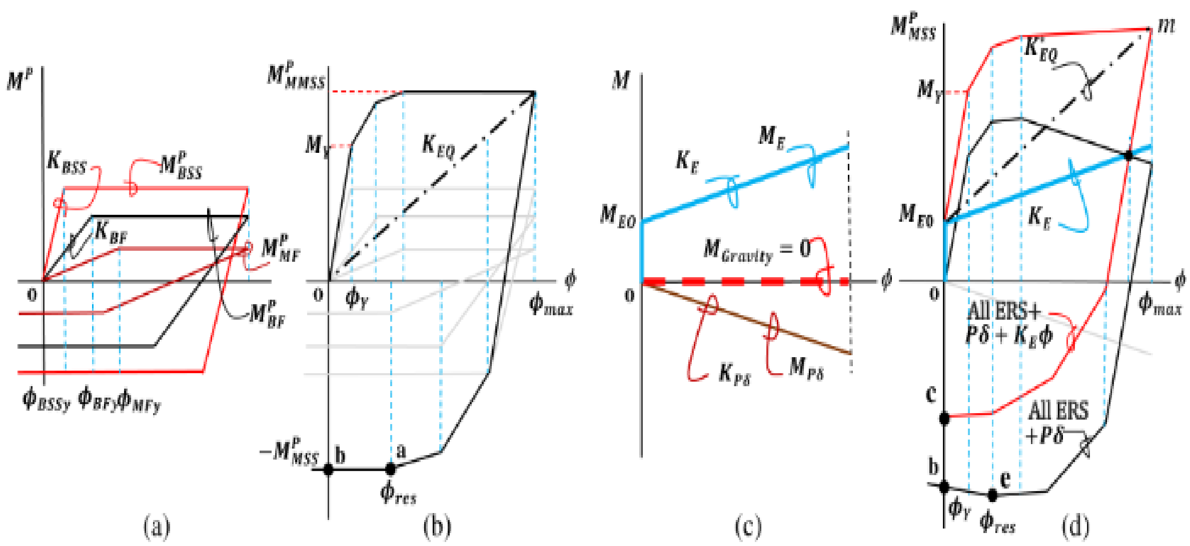

Fig.2- (a) Independent response plots of ductile ERS (b), Combined response curve and equivalent stiffness of plot (a), (c) Bilinear elastic effect, P-delta system with negative stiffness, and zero stiffness structure (d) Combined response curves, (red curve All ERS+Pδ), black curve All ERS+Pδ+Elastic system.

3.2. Diagrammatic Presentation of LSR and GSR

Fig.3(a) shows that the residual moment ***oc*** of Fig.2(d), can be eliminated by increasing the preload by the same amount. This could represent an ideal solution if the resisting capacity at ϕ_{max} is equal to or exceeds the prescribed demand. This eliminates all residual effects and exhausts $M_{E,0}$ to zero. This condition can be improved by reducing the post-earthquake stiffness of all ductile ERSs to zero as delineated by the return load path $(d - M_{E0})$ of Fig.3(b). Option 3(b) implies maintaining a large preload throughout the service life of the structure.

Fig.3(c) presents a prelude to an ideal scenario, Fig.3(d), where recentering by GSR with no preload results in perfect realignment. Note that the flag and pole heights shown in Fig. 3(d) are (M_Y) and $(M_{E,0} = 0)$ respectively. Scheme (d) expends half the effort needed to achieve PERR by scheme (a). Moreover, little to no preload is needed for case (d) realignment, whereas the pole height varies from $(2M_Y)$ to $(3M_Y)$ in the published media. A schematic presentation of solutions of the previous sections is provided in Fig. 4, where a new ductile ERS is also introduced.

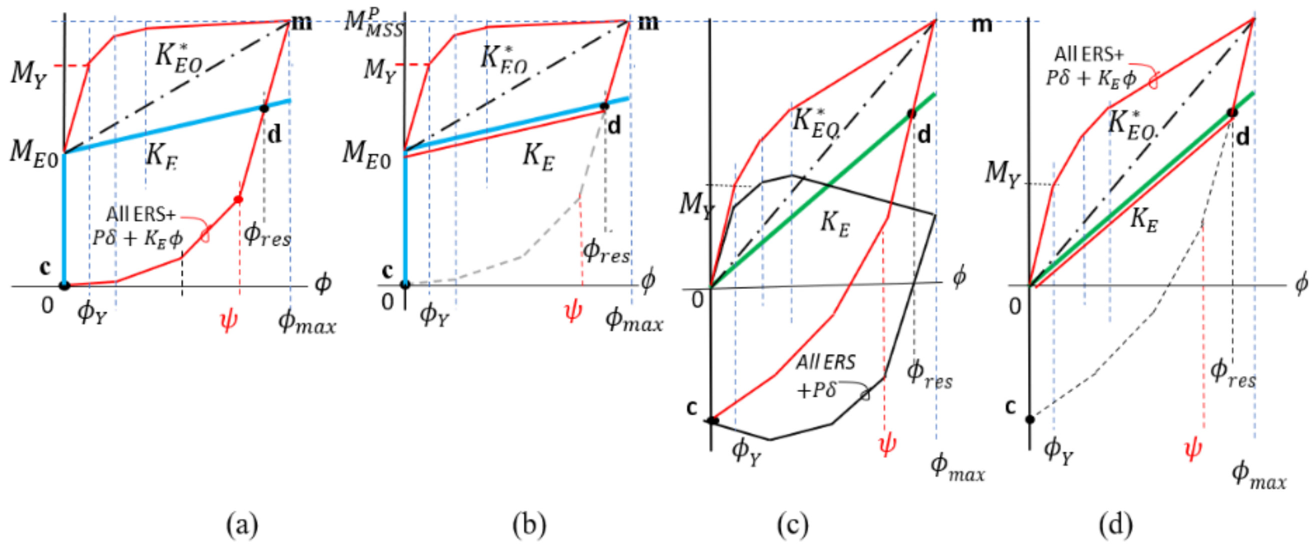

Fig.3- (a) Forced recentering with $M_{E0} = M^P_{MSS}$, (b) Assisted recentering, GSR, with $M_{E0} = M^P_{MSS}$, (c) Forced recentering with $M_{E0} = 0$, (d) Assisted recentering, GSR, with $M_{E0} = 0$

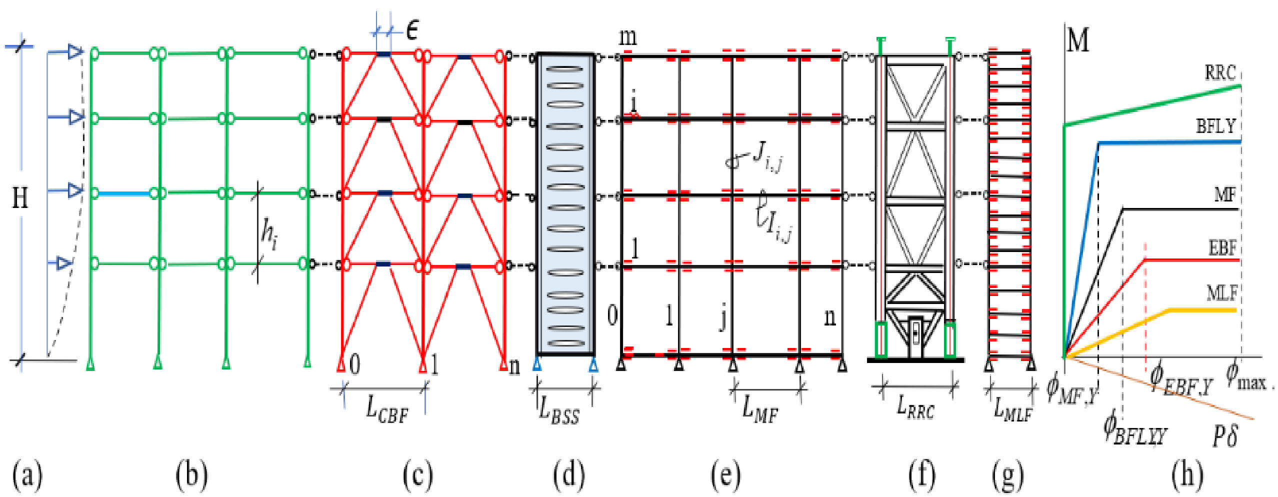

Fig4- (a)Lateral loading, (b) Gravity structure, (c) Low damage CBF, (d) Butterfly steel system, (e) Low damage MF system, (f) Hybrid RRC, (g) Moment ladder frame, (h) Response diagrams

4. The Fail-Safe Concept

A fail-safe device is defined as a control mechanism that allows safe failure with no possibility of physical collapse. Fail-safe devices are meant to safeguard against unforeseen conditions during both earthquakes and PERR operations. Fail-safe devices can also be designed to compensate loss of strength due to utilization of RBS cutouts, slacking of tendons, etc. Fail-safe devices are generally designed to activate either automatically just before $\phi_{max.}$ is realized, or manually during PERR operations. The most basic forms of fail-safe devices consist of the arrangements shown in Fig.5(a) for axial members, the fail-safe flange plates of Fig.5(b) for RBS treated joints, the back-to-back channel sections of Fig. 5(c) with elongated holes on one side for EBFs with disposable link beams and the optional crisscrossing tendons of Fig. 5(b).

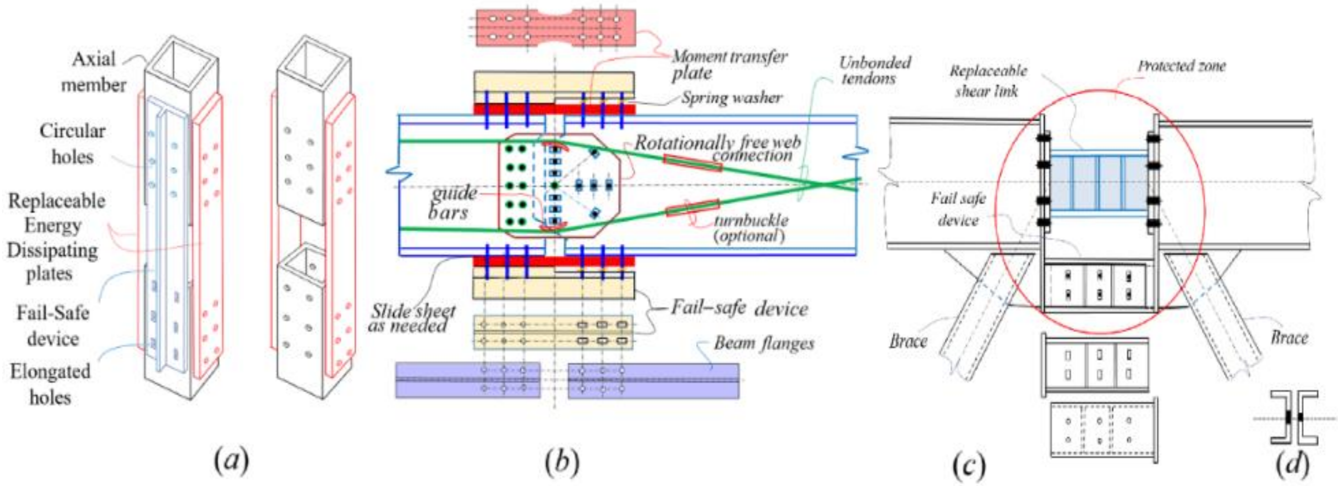

Fig. 5(a) Concept FS arrangement for axial members, (b) Replaceable energy dissipating joint and T-section FS for MF, (c) Replaceable shear link and FS device for EBF, (d) Section through FS device

Conclusions

The effort leading to this presentation was prompted by the notion that SSD can be achieved without resorting to sophisticated analysis or elaborate technologies. Henceforth, the authors hope that this and similar contributions would help provide a basis for development of SSD in future generations of design guidelines. The most relevant technical assessments together with the corresponding findings can be summarized as follows,

- *Advancing the applications of the pushover and hysteresis diagrams*

The Pushover and Hysteresis plots together contain more information than practically utilized, e.g., seismic unloading, realignment, collapse prevention, the *P*-delta effect, and possible repairs can be construed as inherent messages within these diagrams.

- *Sequences of failures of ERS in parallel connection*

The basic rules of sequential failures can best be understood by comparing individual response curves. Sequences of plastic failures of different combinations of ERSs such as MFs, Concentric braced frames, Steel shear walls, Butterfly shear systems, LMF, and RRCs can be easily determined from comparative response plots.

- *SS technologies*

Recently developed GSR, RFA and FS technologies are integral parts of SSD proposed in this work. Purpose-specific details, such as those shown in Figs. 1,5 are meant to reduce/eliminate residual stresses and strains, localize seismic damage, prevent collapse, and facilitate the PERR process.

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References should be cited in the text in square brackets (e.g., [1], [2-4]), numbered according to the order in which they appear in the text. Only list references that are referred in the text. A complete reference should provide enough information to find the article.

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