SEISMIC DESIGN OF STEEL STRUCTURES – A BRIEF OVERVIEW

Dr. Aritra Chatterjee
Assistant Professor
IIT Kharagpur

INTRODUCTION

This article gives a preliminary overview on the intent and basis for seismic structural design, followed by an introduction to different types of steel structural systems used for seismic force resistance, codal provisions to ensure ductility at material, section, component and system scales and ductile detailing requirements. Various codes, standards and guidelines are referenced and discussed preliminarily. However, the referenced codes should not be interpreted as the representative list of standards to be used for seismic design. Utmost care should always be taken to follow all provisions and requirements applying to a project's jurisdiction, including the codes and standards governing at that location. This article is intended to be used for academic purposes only.

HISTORICAL BACKGROUND

Preliminary structural studies on major earthquakes in Japan, New Zealand and USA in the 1920s and 1930s revealed that structures designed to withstand wind loads generally performed better under seismic loads as well. Based on this observation, the first edition of the Uniform Building Code published in 1927 included lateral earthquake loads for structural design, equaling 6-10% of the structural weight. [1]

Theoretical developments in structural dynamics led to the understanding that structural response to ground motion is frequency dependent. However, elastic analysis predictions for peak lateral forces exceeded design capacities typically by a factor of 4, [2] which indicated that portions of a structure were yielding and dissipating energy through inelastic response under earthquakes.

Using Newmark's numerical integration scheme to solve the fundamental equation of motion, [3] it was demonstrated by [2] that inelastic action reduces peak loads due to seismic ground motion. Consider a single degree of freedom (SDOF) oscillator under a ground motion time history. The peak displacement of the oscillator under a seismic ground motion record is approximately in the same range whether it remains elastic or inelastic, and is independent of the yield strength of the oscillator. This observation, known as the "equal displacement approximation", forms the basis for modern force-based seismic design. Although an analytical proof of the equal displacement approximation has not been found, it has been extensively verified numerically (see [4] for review) and experimentally (e.g.). [5]

The equal displacement approximation suggests that an oscillator having an yield capacity equal to the elastic load, and a second oscillator having an yield capacity of *1/R* times the elastic load, produce similar peak displacements under an acceleration time history.

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Therefore, it is acceptable to design the oscillator for a force that is reduced by a factor of R compared to elastic demands, if and only if the oscillator has a ductility capacity equaling or exceeding its yield displacement times R (see Fig. 1). This quantity R, known as response reduction factor, has traditionally been prescribed in design codes based on past engineering experience, and is estimated by an incremental dynamic approach [6] outlined in [7] for new structural systems.

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RESPONSE REDUCTION '*R*' FACTOR BASED APPROACH TO SEISMIC DESIGN

Force based design that is commonly used in earthquake resistant design standards including IS 1893 (Part 1):2016 [8] and ASCE 7-2016, [9] utilizes a response reduction factor R which is explained in Fig. 1. The elastic base shear expected on a system under a design earthquake is denoted as V_E. If the entire structural system remained elastic under the effect of an earthquake, the shear force generated at its base would equal V_E. However, material strength or section size requirements to resist forces resulting from elastic base shear V_E are usually so large, that they are impractical or unfeasible to provide in real structures. Therefore the philosophy for designing such structures is that portions of the system will yield and undergo plastic response under design earthquakes. It is through this plastic response that structural systems dissipate energy inputted by earthquake ground motion.

Accordingly, a designated portion of the structural system, known as the lateral force resisting system (LFRS) or the energy dissipative system, is designed to plastify under earthquake loads. This system acts as a "Structural Fuse" and limits force demands on parts of the structural system that are in series in its load path. Structural components in series with the LFRS are subjected to forces equaling the maximum capacity of the LFRS, which equals the LFRS yield capacity multiplied by an appropriate overstrength factor Ω_0 (see Fig. 1). This design approach is known as "Capacity Design" and is described in IRC SP-114:2018 Section 7.3. [10]

To account for deviations from the equal displacement approximation, a displacement amplification factor C_d (see Fig. 1) is provided in US design standards. Portions of the structural system other than the designated LFRS, for example gravity columns, are to be designed for the imposed peak inelastic displacement of the LFRS. Fig. 1 explains response reduction, overstrength and deflection amplification factors as described in FEMA P-695. [7]

The designated lateral force resisting system or "Structural Fuse" needs to possess adequate

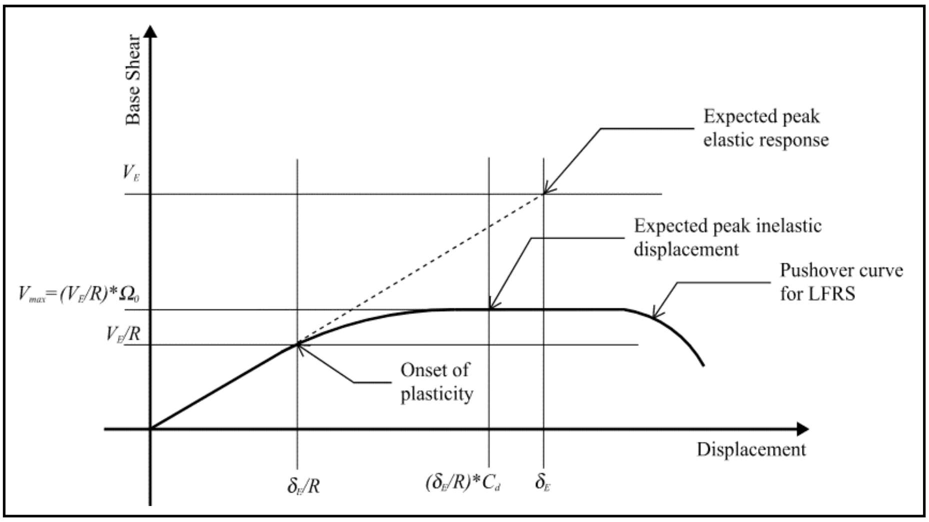

Fig. 1: Graphical representation of response reduction factor R, overstrength factor Ω_0 and deflection amplification factor C_d

ductility to inelastically dissipate the energy input from seismic ground motion without undergoing rupture, instability or collapse. In the following section, representative energy dissipative systems for steel structures are introduced.

STEEL SYSTEMS COMMONLY USED FOR SEISMIC ENERGY DISSIPATION

Designated lateral force resisting systems for steel structures are listed in Fig. 2, including response reduction factors per IS 1893 (Part 1):2016 and ASCE 7-2016. Also included are deflection amplification factor C_d and overstrength factor Ω_0 per ASCE 7-2016. Overstrength factor for steel systems is uniformly recommended as 1.25 in IRC SP:114-2018 Section 4.2.4 Note v.

DUCTILITY AND DETAILING REQUIREMENTS FOR ENERGY DISSIPATIVE SYSTEMS BUILT USING STRUCTURAL STEEL

Steel material used for seismic energy dissipative elements should conform to codal requirements to ensure adequate ductility for the required energy dissipative capacity. Typically, standard material permitted to be used for structural steel elements (for example, steel complying with IS 2062) [12] are permitted to be used for seismic applications due to their adequate ductility. Per IS 800:2007 section 4.5.2, the stress-strain diagram for the steel at yield stress is required to have a plateau extending for at least six times the yield strain to ensure plastic section behaviour. Bracing members used in Special Concentrically

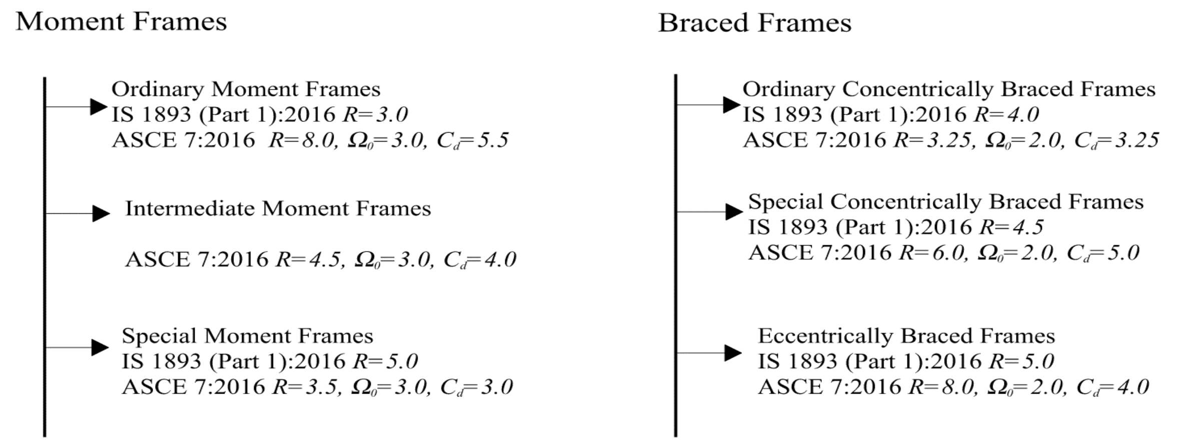

Fig. 2: Steel LFRS and associated factors per Indian and American design standards

In addition to the systems listed in Fig. 2, shear wall systems such as special plate shear walls, composite ordinary shear walls, composite special shear walls and composite plate shear walls (either encased or filled with concrete) are covered in ANSI/AISC 341-16. [11] Composite systems consist of steel framing and/or sheets in addition to reinforced concrete.

Response reduction '*R*' factors for steel energy dissipative systems (Fig. 2) correspond to expected levels of ductility or energy dissipative capacities. Specific requirements to justify the given response reduction factors are rotational ductility at moment frame connections and axial force ductility in bracing components. A brief overview of codal provisions intended to ensure the availability of this ductility is discussed in the next section.

Braced Frames (SCBF) and members used in Special Moment Frames (SMF) are required to be constructed of E250 steel per IS 800:2007.

Similarly, material ductility is required at energy dissipative connection elements. Per IS 800:2007 provision 12.4.1, all bolts designed to resist earthquake loads are to be fully tensioned high strength friction grip bolts. Per IS 800:2007 provision 12.4.2, all welds used in seismic load resisting frames are to be complete joint penetration (CJP) butt welds, except in column splices, where partial joint penetration (PJP) butt welds are permitted if the joint strength is atleast twice the required strength, per section 12.5.2.2.

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are required to meet Chapter A provisions in ANSI/AISC 341-16 including 22% minimum elongation for 480 MPa welds, and specified Charpy V-Notch toughness. Demand critical welds are to be specifically identified on structural drawings. Further, connection details used in intermediate and special moment frames must conform with prequalified connection requirements described in ANSI/AISC 358-16,[13] or be tested to ensure adequate ductility per provisions given in Chapter K of ANSI/AISC 341-16.

In addition to material scale, adequate ductility needs to be ensured at section, component and system scales to justify response reduction factors explained in Fig. 1 and listed in Fig. 2. Steel sections that are used in energy dissipative systems are required to have sufficient compactness such that local buckling does not prevent the required energy dissipative capacity to be developed.

To ensure that local buckling does not prevent the steel section from dissipating the required amount of energy under earthquake loading, IRC SP:114-2018 stipulates that "only plastic and compact sections shall be used in potential plastic hinge formation zone". Section classification for Indian Steel Sections are provided in Table 2 of IS 800:2007. Similarly, ANSI/AISI 341-16 table D1.1 specifies width to thickness ratio limits for moderate and highly ductile members.

IS 800:2007 stipulates that bracing members shall mandatorily have plastic sections in Special Concentrically Braced Frames (SCBF), whereas they are permitted to have plastic, compact or semi-compact sections in Ordinary Concentrically Braced Frames (OCBF). Column sections used in SCBF are mandated to be plastic per IS 800:2007 Section 12.8.4.1.

It is to be ensured that structural components that are designated for energy dissipation do not undergo instability failure. Accordingly, per IS 800:2007, slenderness ratio of bracing members should not exceed 120 for OCBF and 160 for SCBF. Similarly, in ANSI/AISI 341-16, slenderness ratio of diagonal braces in SCBF is limited to 200. ANSI/AISI 341-16 also specifies bracing requirements for moderately and highly ductile members at specified maximum spacing noted in Chapter D. Bracing required in steel beams shall brace both flanges, or point-brace the cross section against torsion. Special bracing is required at locations where plastic hinges are expected to form.

Members designated as energy dissipative elements are required to fail in ductile modes only - brittle failures are absolutely not permitted. Accordingly, bracing elements in braced frames are to be designed such that gross tensile yielding is the governing failure mode. Net tensile rupture should never govern in such elements.

Designated energy dissipative locations should not undergo rupture or fracture due to stress concentration or initial 'weak spots'. To ensure this, ANSI/AISI 341-16 chapter D prohibits fabrication or erection procedures (such as welding) at locations identified as "protected zones" where plastic energy dissipative behaviour is expected (for example, plastic hinge location near moment connections on moment frame beams or axial yielding locations on bracing members).

Structural elements that are in series with the designated energy dissipative section are to be capacity designed to resist the maximum force that can be developed in the system, as discussed in Fig. 1. Examples of capacity designed elements include, but are not limited to:

1. Column bases (including anchor bolts) are to be capacity designed for moment and shear equaling at least 1.2 times the full plastic moment capacity and shear capacity of the column respectively, per IS 800:2007 section 12.12.
2. Bracing connections in OCBF and SCBF are to be designed to withstand minimum

of (a) 1.2 and 1.1 times the brace gross section yielding capacity respectively and (b) maximum force that can be transferred to the brace by the system, per IS 800:2007 Sections 12.7.3 and 12.8.3

3. Rigid moment connections in ordinary moment frames (OMF) and SMF are to be designed to withstand 1.2 times the full plastic moment capacity of the connected beam, per IS 800:2007 Section 12.10.2.1 and 12.11.2.1
4. The summed moment capacity of columns above and below beam centerline in SMF are required to be designed for capacity greater than or equal to 1.2 times the summed moment capacities of beams at the connection intersection per IS 800:2007 Section 12.11.3.2. This is known as "strong-column weak-beam" concept.

CONCLUSIONS

The basis for ductile design of seismic systems is to permit some plasticity and energy dissipation, with a primary requirement of adequate ductility at designated energy dissipative elements. In addition, it is of critical importance that a continuous load path for seismic force flow is identified and properly designed. The load path should initiate at the point of generation of inertial forces and should be continuously followed through the diaphragm, to collector elements, the designated energy dissipative system and all the way to the foundation. All elements in this load path are to be capacity designed for the maximum expected capacity of the energy dissipative system (including overstrength). The energy dissipative system is to be designed for adequate ductility per relevant codal provisions, some of which were briefly introduced in this paper. Displacement compatibility should be adequately considered by designing all elements for expected imposed deformations, including unusual effects such as torsion, higher mode effects or soft story modes. Precise engineering judgment along with close adherence to all applicable and available design standards and technical literature is crucial to ensure safety from structural collapse due to seismic loads.

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