ON ASEISMIC DESIGN

P. Mueller[1]

SUMMARY

This paper represents an attempt to establish a few simple basic concepts along with a terminology that are helpful to understand the effect of the sequence of plastification on the seismic behavior of inelastic systems and to formulate some guidelines. Enforcing a preselected sequence of plastification is not only important for ductile systems with large inelastic deformations, but offers also advantages to systems of limited ductility appropriate for regions of moderate seismicity.

INTRODUCTION

At code specified strength levels, buildings must be provided with good ductility and inelastic energy dissipation capacity to withstand major earthquakes. The objective of good member design is to design a hierarchy of failure modes into the member ensuring that the member reaches its strength in a ductile mode (e.g. in flexure rather than shear). Similarly, the objective of good system design is to design a hierarchy of member strengths into the structural system enforcing a sequence of plastification with good inelastic deformation, energy dissipation, and stiffness characteristics (Ref. 1). Present code procedures concentrate almost solely on the member level and largely ignore the effect of the sequence of plastification on system "ductility". For member strength is simply provided proportionally to the linear-elastic member force distribution rather than with the purpose to enforce a preselected sequence of plastification.

Inelastic aseismic design procedures abandoning conventional member proportioning, on the other hand, leave the designer with much more freedom and, hence, require increased understanding of the seismic behavior of inelastic systems. Which sequence of plastification should be enforced? Which distribution of member strengths does result in optimum response? This paper represents an attempt to establish a few simple basic concepts along with a terminology that are helpful to understand the effects of the sequence of plastification on the seismic behavior of inelastic systems and to formulate some guidelines. Although one might think that design procedures enforcing a preselected sequence of plastification are most urgently needed for ductile systems experiencing large inelastic deformations, they are actually as beneficial in the range of moderate inelastic deformations. Buildings of limited ductility appropriate for regions of low to moderate seismicity may therefore profit significantly from such procedures. A more

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[1]Associate Professor, Lehigh University, Bethlehem, Pennsylvania, USA

detailed presentaton of the following material is given in Ref. 2.

SEISMIC BEHAVIOR OF INELASTIC SYSTEMS

The sequence of plastification significantly influences the seismic behavior of systems. To understand these effects, it is helpful to distinguish two aspects of the sequence of plastification: the type of yield mechanism that develops and the extent of the range of contained yielding in the overall resistance-deformation relationship. Attainment of the ultimate lateral strength of a structure is characterized by the formation of a complete (yield) mechanism. Assuming elastoplastic member properties, the resistance does no longer increase and the tangent stiffness is zero. The kinematics of the mechanism describe the distribution of the plastic deformations occurring after attainment of the ultimate strength. It is customary to distinguish between static and dynamic degrees of freedom (DOF), the latter being those DOF essential to capture the dynamic aspects of response. Similarly, it is useful to introduce the DOF of the complete mechanism as the plastic DOF, because they represent those DOF essential to capture the inelastic aspects of response.

Formation of a complete mechanism may or may not be preceded by a distinct range of contained yielding, in which the inelastic deformations of the yielding members are still restricted and controlled by elastic members. Overall deformations can only increase, if also the deformations of the elastic members and, hence, the resistance increase; the tangent stiffness is still positive. The terminology used is illustrated in Fig. 1. Much of the sometimes puzzling behavior of inelastic multi-degree-of-freedom (MDOF) systems can be understood in terms of the number of DOF of the complete mechanism and the behavior of single-degree-of-freedom (SDOF) systems with similar resistance-deformation relationship.

In the following discussion of these effects only quite general classes of structural elements are distinguished. A geometrical classification includes horizontal and vertical elements. A functional classification distinguishes primary gravity load bearing elements (critical for overall stability), bracing elements (adding lateral stiffness and strength), and primary energy dissipating elements (suited as structural fuses and hystetic dampers). One objective of this discussion is to identify the latter class of elements in terms of the former.

Types of Yield Mechanisms

Two basic types of yield mechanisms can be distinguished: S-mechanisms and O-mechanisms. All other mechanisms can be considered as combinations of the two basic types. In S-mechanisms (Fig. 2) only vertical elements yield, while horizontal elements remain elastic. Each story contains a complete mechanism and can indepedently translate in the direction of the ground motion. In the plane, such Story- mechanisms have as many DOF as stories. In O-mechanisms (Fig. 3) all horizontal elements yield. Vertical elements are elastic except at their base and rotate rigidly about their base. In the plane, such Overall-mechanisms have only one DOF.

Structures responding in a S-mechanism are true MDOF systems. Although complete mechanisms do not usually form simultaneously in all stories, a complete mechanism forms in virtually every story at some time instant during the response. It is this and only this type of mechanism that the widely used shear beam model accurately represents. It is well known that the distribution of interstory displacements and ductility ratios of shear beams and of frames with plastic hinges in columns is extremely sensitive to details of the ground motion. Precast panel walls sliding along horizontal connections (Fig. 2a) exhibit the same behavior (Ref. 3, 4). Inelastic interstory displacements tend to concentrate into different stories for different ground motions (Fig. 4). Even worse, their distribution over the height also changes significantly for different intensities of the same ground motion (Fig. 5).

Structures responding in an O-mechanism behave completely differently, because they have only one plastic DOF. The elastic, rigidly rotating upper parts of the vertical elements enforce a uniform distribution of the interstory displacements occurring after attainment of the ultimate lateral strength. Ref. 5 shows for frames that shear beams with their uncoupled story DOF are inadequate models for O-mechanism response, while generalized SDOF models derived from equivalent lateral load analysis show quite good agreement with member-by-member analysis. Fig. 6 illustrates similar trends for a coupled wall system: the relative distribution of ductility demands over the height can be found with sufficient accuracy with an equivalent static lateral load analysis (inelastic) using a triangular lateral load and the maximum top deflection found from the dynamic analysis (Ref. 2). Note also that this relative distribution is quite insensitive to ground motion intensity. It can be concluded that in O-mechanism response, the relative distribution of inelastic deformations over the height is primarily controlled by the elastic parts of the vertical elements rather than by the details of the ground motion.

Range of Contained Yielding

Fig. 7 compares systems without and with a distinct range of contained yielding in primary energy dissipating elements, that is systems with elastoplastic (Fig. 7a) and trilinear (Fig. 7b) idealized overall resistance-deformation relationships. None of the cases shown in Fig. 7b exhibits shake-down under cyclic loading. Assuming similar overall strength and initial stiffness, it is evident from Fig. 7 that the trilinear system starts to yield at smaller deformations and forms a complete mechanism only after larger deformations than the elastoplastic system. The earlier yielding introduces inelastic energy dissipation earlier in response and in more cycles. The later formation of a complete mechanism implies that a restoring force from still elastic elements is available for larger deformations and in more cycles. The effectiveness of this restoring force (i.e. of a positive post-yielding slope) in centering vibrations and preventing accumulation of plastic drift, is illustrated in Fig. 8, which compares response time histories of an elastoplastic and a bilinear ($p=0.1$) SDOF oscillator (Ref. 6). These reasons explain the results from inelastic dynamic MDOF analysis of coupled wall systems and frames, which show that a distinct range of contained yielding improves seismic behavior at moderate inelastic deformations while not worsening it at large inelastic deformations (Ref. 7).

GUIDELINES FOR SEQUENCE OF PLASTIFICATION

The primary reason for enforcing a preselected sequence of plastification is reduction of uncertainty. Prime thrust of the following guidelines and criteria is to achieve a system that responds as predictably as possible to ground motions with differing and unpredictable details. In inelastic response, force levels are primarily controlled by the actual strength of the yielding members/ sections. In other words, they are primarily controlled by the designer rather than by the earthquake, provided he knows which members/sections will yield. The type of mechanism (particularly the number of DOF) determines whether the relative distribution of inelastic deformations over the height is controlled primarily by the erratic details of the ground motion (S-mechanism) or primarily by the kinematics of the mechanism (O-mechanisms). Accumulation of plastic drift is primarily controlled by the erratic details of the ground motion during excursions into a complete mechanism, while it is controlled by the restoring force of still elastic elements during excursions into the range of contained yielding. Extending the range of contained yielding increases the number of cycles in which an elastic restoring force centers the vibrations. In addition to improving the stiffness characteristics, this also improves the energy dissipation characteristics by increasing the number of cycles in which yielding takes place. Based on these observations, the following guidelines regarding sequence of plastification are proposed:

- Enforce O-mechanisms (or mechanisms with the fewest possible number of DOF) and keep vertical elements elastic as long as possible at the base and top and always in between.
- Introduce a distinct range of contained yielding in primary energy dissipating elements and maintain a restoring force from still elastic elements as long as possible.

It remains to identify elements that are suited as primary energy dissipating elements. The following criteria are proposed:

- Their yielding must be restricted by other still elastic elements
- They should not be primary gravity load bearing elements except for low-rise structures
- They must be ductile and exhibit full and stable hysteresis loops
- They should provide a significant portion of the overall stiffness and yet be relatively flexible

The last criterion is justified in Ref. 2. These seemingly contradictory criteria are usually met by bracing elements and horizontal elements. These guidelines for the sequence of plastification agree with and include generally accepted aseismic design philosophies as those sketched in Fig. 7b. They represent an attempt to distill the common characteristics from these desirable sequences of plastification. The general formulation should encourage incorporating these characteristics in new ways into new systems.

OPTIMUM STRENGTH AND STIFFNESS DISTRIBUTION

The question of prime practical importance is, of course, how to enforce the recommended sequence of plastification. At the member level, it is common practice to use different safety factors for desirable and undesirable modes of failure (e.g. for flexure and shear). Similarly, at the system level the selected sequence of plastificaton can be enforced using different force reduction factors as illustrated in Fig. 9. R_y reduces the contribution of primary energy dissipating elements to overall resistance from the linear-elastic level to the yield level (point Y). R_p reduces the contribution of those elements/sections, whose yielding completes the mechanism, from the linear-elastic level to the yield level (point P). A third factor, R_e, reduces the linear-elastic force response to the yield level required for those elements that should remain elastic also after a complete mechanism has formed. The force reduction factor R for lateral seismic forces, which is specified in the ATC 3 provisions (Ref.8), is related to R_y and R_p by the simple expression shown in Fig. 9.

The more R_y exceeds R_p, R_e, the better predictable is the sequence of plastification. However, the larger $R_y/R_p= \Delta_p/\Delta_y$, the more distinct is also the range of contained yielding. Fortunately, this actually improves the energy dissipation and stiffness characteristics of the system: Judging from results on 16 coupled structural walls and 2 frames, the optimum relative strength distribution appears to lie in the range of R_y/R_p= 2 to 4 (Ref. 4, 7). The presented format would allow reporting and accumulating more data in a form that is general enough for code implementation and related to the ATC 3 (Ref. 8) format.

Assessing current design practice, Galambos, et. al. (Ref. 9) report practically similar reliability indices for beams and columns in reinforced concrete as well as steel frames. However, if the probability of yielding is similar for all members, the type of the developing mechanism primarily depends on the random variations in the details of the ground motion, in higher mode effects, and between calculated and actual strengths and stiffnesses. Moveover, there is also no distinct range of contained yielding. Thus current practice of using a single force reduction factor $R_y=R_p=R_e=R$ precisely leads to least predictable response. For systems with large inelastic deformations the advantage of considerably differing R_y and R_p lies primarily in the improved predictability of the sequence of plastification. For systems with small to intermediate inelastic deformations, however, there are additional benefits: the improved energy dissipation and stiffness characteristics in the range of contained yielding and the possibility of activating the full energy dissipation capacity of ductile elements, while keeping brittle elements elastic. Achieving systems with limited overall "ductility" through proper combination of fully ductile and rather brittle elements may be an interesting alternative for regions of moderate seismicity in view of the difficulties in establishing quantitative relationships between "ductility" and detailing requirements. Some guidelines regarding the optimum stiffness distribution are given in Ref. 2.

CONCLUSIONS

Review of results from inelastic dynamic analysis shows that quite different structural systems show similar behavioral trends regarding sequence of plastification. Overall seismic response characteristics primarily depend on the type of mechanism that develops, and on the extent of the range of contained yielding. This observation allows formulation of general yet simple guidelines for the sequence of plastification. The relative member strength distribution leading to optimum inelastic deformation, energy dissipation, and stiffness characteristics deviates significantly from the linear-elastic member force distribution.

ACKNOWLEDGEMENT

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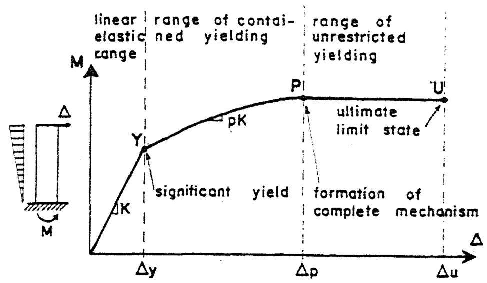

FIG. 1 CONCEPTS AND TERMINOLOGY

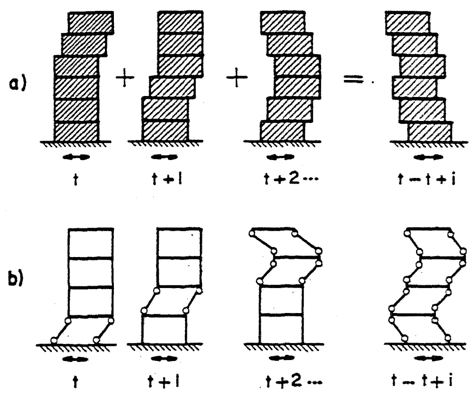

FIG. 2 S-MECHANISMS

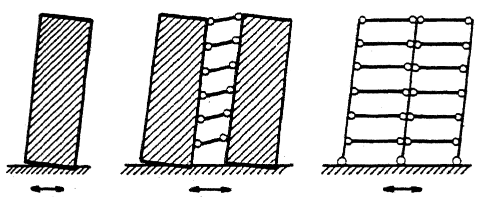

FIG. 3 O-MECHANISMS

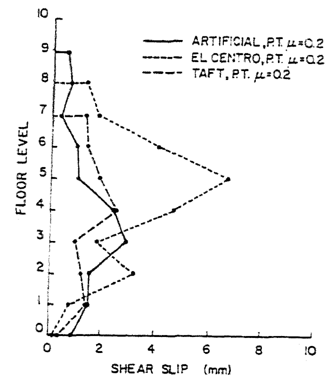

FIG. 4 SHEAR SLIP ENVELOPES FOR POST-TENSIONED PRECAST WALL FOR DIFFERENT GROUNDMOTIONS (.25g PEAK ACC.) (REF. 3)

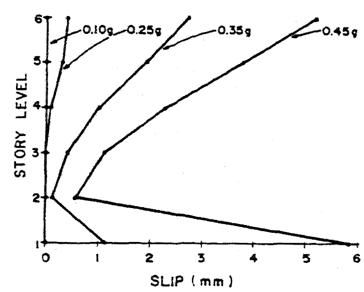

FIG. 5 SHEAR SLIP ENVELOPES FOR REINFORCED PRECAST WALL FOR DIFFERENT INTENSITIES OF EL CENTRO

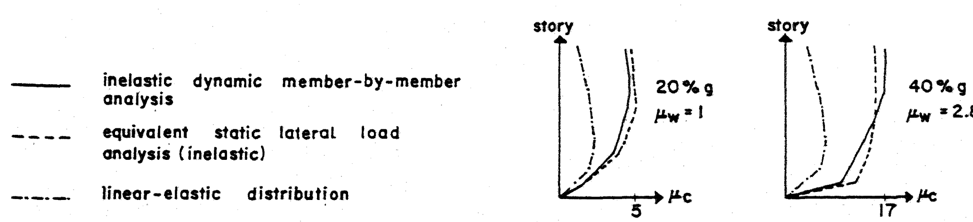

FIG. 6 ENVELOPES OF DUCTILITY DEMANDS FOR COUPLING ELEMENTS OF COUPLED WALL SYSTEM (EL CENTRO)

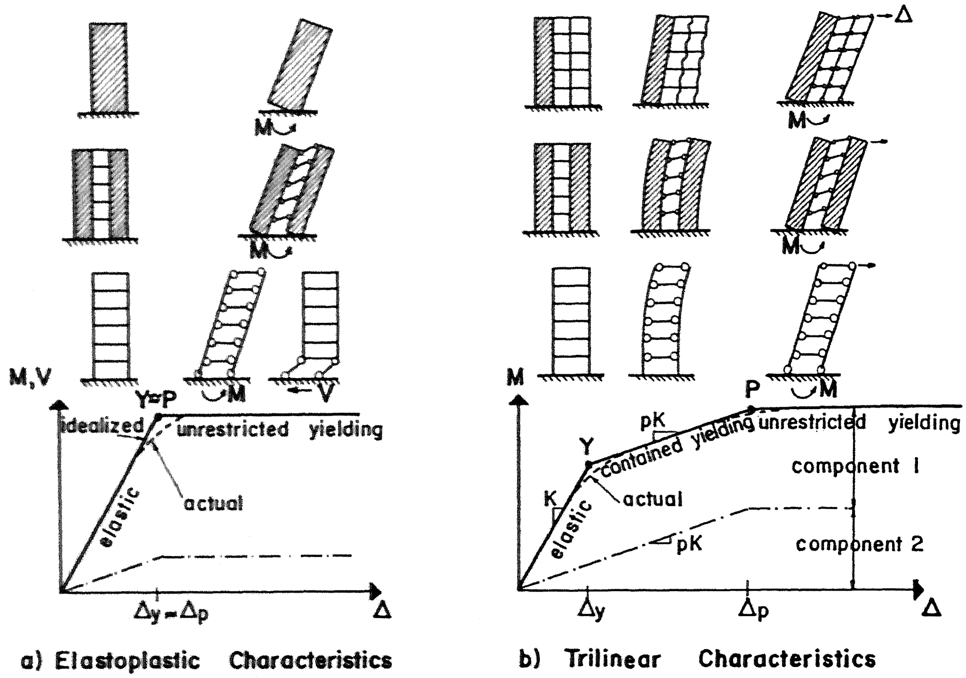

FIG. 7 IDEALIZED OVERALL RESISTANCE-DEFORMATION CHARACTERISTICS

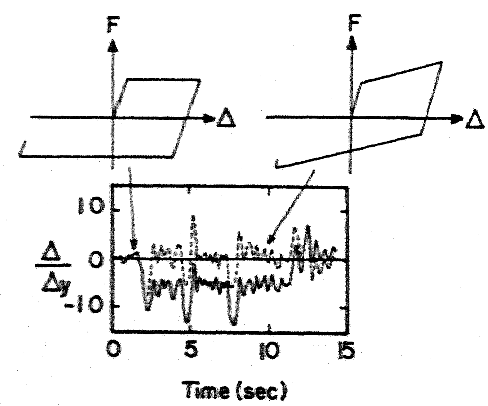

FIG. 8 RESPONSE OF SDOF SYSTEMS TO KERN COUNTY EARTHQUAKE (REF.6)

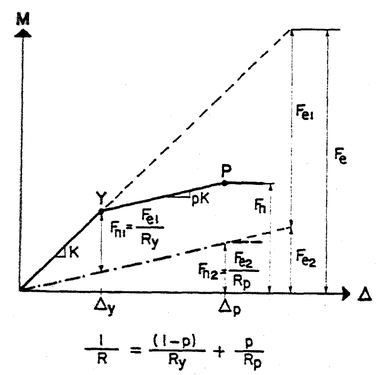

FIG. 9 FORCE REDUCTION FACTORS FOR TRILINEAR OVERALL CHARACTERISTICS