DIPARTIMENTO DI INGEGNERIA CIVILE

Dottorato di Ricerca in Ingegneria delle Strutture e del Recupero Edilizio e Urbano

XIII Ciclo N.S. (2012-2014)

THEORY OF PLASTIC MECHANISM CONTROL FOR ECCENTRICALLY BRACED FRAMES: CLOSED FORM SOLUTION

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Abstract

Collapse mechanism control is universally recognized as one of the primary goals of the structural design process. The aim is to avoid partial collapse mechanisms, such as soft storey mechanisms, which are unsatisfactory in terms of energy dissipation capacity.

The optimization of the seismic structural response is, conversely, obtained when a collapse mechanism of global type is developed [1-3], because, in such case, all the dissipative zones are involved in the corresponding pattern of yielding, leaving all the other structural parts in elastic range.

These are the basis of the so called "capacity design" principles, which state that dissipative zones have to be designed according to the internal actions arising from the design seismic forces, while the non-dissipative zones have to be proportioned on the basis of the maximum internal actions which dissipative ones are able to transmit in the fully yielded and strain-hardened state.

In order to decrease the probability of plastic hinge formation in columns, MR-Frames must be designed to have strong columns and weak beams. To this scope, different simplified design criteria have been proposed [4-10] and the so-called beam-column hierarchy criterion has been introduced in Eurocode 8 [11].

Even though studies on this topic started several decades ago mainly with reference to reinforced concrete structures [9, 12-14] and, in particular, in New Zealand where the capacity design procedure found its codification since 1982 [15], codified design rules included in Eurocode 8 as well as similar procedures adopted by other codes cannot achieve the design goal, i.e. the development of a global type mechanism.

There are a number of reasons why the beam-column hierarchy criterion cannot achieve the above mentioned design goal and these have been widely discussed both with reference to reinforced concrete frames [16] and to steel frames [17]. In fact, it is well known that such hierarchy criterion is able to prevent soft-storey mechanisms, but is not adequate to assure a collapse mechanism of global type [5, 7-10].

Among the different reasons leading the beam-column hierarchy criterion to fail in the achievement of the design goal, probably the most important, and difficult to be accounted for in a simplified design approach, is the shifting of the contraflexure point in columns during the seismic excitation. This considerable shifting leads to a bending moment distribution substantially different from that resulting from code-prescribed design rules [18-19]. The shift of the contraflexure point is caused by the formation of hinges in beams adjacent to the column and even in part of the columns. All these factors alter the stiffness of beam-column subassemblage, hence the moment distribution.

The main reason why the above issue cannot be accounted for by means of a simplified design rules, such as the beam-column hierarchy criterion, is that the second principle of capacity design [20] cannot be easily applied in case of multiple resisting mechanisms not located in series. In fact, according to the second principle of capacity design, non-dissipative zones (i.e. the columns in case of MR-Frames) need to be designed considering the maximum internal actions which the dissipative zones (i.e. the beam ends in case of MR-Frames) are able to transmit at their ultimate conditions. The beam-column hierarchy criterion is based on the possibility to accurately evaluate, at any beam-to-column joint, the sum of the bending moments which the beams are able to transmit when ultimate conditions occur, but, conversely, because of the shifting of contraflexure point in columns during the seismic excitation, it is practically impossible to predict how the above sum is shared between the end sections of the top and bottom column converging in the joint [2-10]. For this reason, it is well known that the beam-column hierarchy criterion, based on simple joint equilibrium, is only able to prevent "soft storey" mechanisms, but it does not allow the development of a collapse mechanism of global type.

For this reason, a rigorous design procedure, based on the kinematic theorem of plastic collapse, has been presented in 1997 by Mazzolani and Piluso [17], aiming to guarantee a collapse mechanism of global type where plastic hinges develop at the beam ends only, while all the columns remain in elastic range. Obviously, exception is made for base section of first storey columns, leading to a kinematic mechanism. Starting from this first work, the "Theory of Plastic Mechanism Control" (TPCM) has been outlined as a useful tool for the seismic design of steel structures. It consists on the extension of the kinematic theorem of plastic collapse to the concept of mechanism equilibrium curve. In fact, for any given structural typology, the design conditions to be applied in order to prevent undesired collapse mechanisms can be derived by imposing that the mechanism equilibrium curve corresponding to the global mechanism has to be located below those corresponding to all the other undesired mechanisms up to a top sway displacement level compatible with the local ductility supply of dissipative zones. For this reason, in case of complex resisting mechanisms, a rigorous application of capacity design principles requires more sophisticated design procedures. This is the case of the column design aiming to assure a collapse mechanism of global type, i.e. a collapse mechanism assuring the dissipation of the earthquake input energy by the participation of all the dissipative zones while all the non-dissipative zones remain in elastic range.

This design approach was successively extended to MRFs with semi-rigid connections [21], MRFs with RBS connections [22], EB-Frames with horizontal links (i.e. split-K scheme and D-scheme) [23-24] or with inverted Y scheme [25-26], knee-braced frames [27], dissipative truss-moment frames DTMFs [28-29] MRF-CBF dual systems [30].

The problem of failure mode control aiming to assure a strong column-weak beam seismic behaviour has been also faced by Lee and Goel [31] with reference to moment-resisting frames but by means of a static approach.

Starting from the above background, recent important improvement to the original Theory of Plastic Mechanism Control have been achieved [32]. In particular, by means of new considerations regarding collapse mechanism typologies, a closed form solution has been found [32]. The design conditions to be satisfied to prevent undesired collapse mechanisms can now be solved without any iterative procedure, so that the unknown of the design problem, i.e. column sections at each storey, can now be directly derived.

In this work the new advances in the "Theory of Plastic Mechanism Control" in closed form solution are reported and pointed out. In addition, particular reference is made to the closed form TPMC applied to Moment Resisting Frame-Eccentrically Braced Frames dual systems (MRF-EBFs dual systems).

In the framework of seismic resistant structure, Eccentrically Braced Frames (EBFs) constitute a quite recent structural typology. They gained prominence thanks to the study of Popov and Kasai [33-35]. This structural typology is well suited for tall buildings located in areas of high seismic intensity. For this reason, EBFs are especially widespread in USA and New Zealand where the recent Christchurch earthquake of the February 11th 2011 put to the test a great number of structures. In particular, this unfortunate event allowed testing on real scale the damage a high intensity earthquake is able to bring on EBF steel frames (Figure 1.4). Since this earthquake, New Zealand Heavy Engineering Research Association launched rules to the Seismic

Design of Eccentrically Braced Frames [36]. As regards their working under seismic actions, EBFs constitute a suitable compromise between seismic resistant MR-frames and concentrically braced frames because they exhibit both adequate lateral stiffness [37-38], due to the high contribution coming from the diagonal braces, and ductile behaviour, due to the ability of the links, constituting the dissipative zones of this structural typology, in developing wide and stable hysteresis loops [33-39]. Therefore, the coupling of MRF and EBF constitute an excellent dual system where the primary structural system is constituted by the EBF part, and a secondary fail-safe system is constituted by the MRF part. This secondary one can be considered as an additional dissipative system where plastic hinges are concentrated at the beam ends. However, the main dissipative system is constituted by the link members located in the braced bay of MRF-EBF dual systems which can be horizontal (K-scheme, D-scheme and V-scheme) or vertical (inverted Y-scheme) [11]. In this framework particular attentions needs to be applied to the connections of diagonals constituting the bracing system. In fact, the practice is divided between those who privilege pinned connection and those who privilege fixed connection at the brace bases. This second solution is undoubtedly stiffer but shows many problems in term of constructive details. In addition, being the braces able to transmit not only the axial force but also the bending moment, they have to be considered, as same as columns in the framework of the design procedure which assure a collapse mechanism of global type [23], [40]. This problem has been faced by Mastranderea and Piluso [39], who developed the TPMC design procedure for simple EBFs with fixed base brace sections. Conversely, in this work diagonals constituting the bracing system are considered as pinned at their bases; it means that they are assumed unable to transmit the bending moments and, therefore, are modelled with actual hinges in the structural scheme with some relevant advantages also in the design procedure.

The first aim of this work is to provide a complete procedure to design Moment Resisting Frame-Eccentrically Braced Frames dual systems (MRF-EBFs dual systems) finalized to the development of a collapse mechanism of global type. To this scope, the procedure starts from the design of dissipative zones, called links, switch to the definition of local hierarchy criteria needed to assure that yielding is concentrated only in the link while the other members remain in elastic range and leads to the design of column sections needed to assure the development of a collapse mechanism of global type by means of TPMC.

From its side, Eurocode 8, which is the standard reference to the design of structures in Europe, does not provide specific hierarchy criteria for MRF-EBF dual systems, so that the design procedure is based on simplified hierarchy criteria following the same principle also applied in case of MRFs. In particular, the application rule to design the columns is based on the use of an amplifying factor whose aim is the prevention of yielding or buckling of non-dissipative elements, when the most stressed dissipative zone is yielded and strain-hardened up to its ultimate condition. Regarding non-dissipative elements, i.e. columns, beams and diagonal braces have to be designed with the most unfavourable combination of the axial force and bending moments.

As preliminarily discussed, Eurocode proposal are able to avoid soft storey mechanisms but are not able to design structures showing a collapse mechanism of global type. For this reason, a number of MRF-EBFs dual systems have been designed with both the procedures, i.e. TPMC and Eurocode 8, with the scope to point out, on one hand, the accuracy of the proposed design procedure (TPMC) which always allow the development of a global mechanism and on the other hand, to compare the structural performance of the designed structures against destructive seismic events. In particular, the validation of the proposed design procedure and the comparison in terms of seismic performance between the structure designed by TPMC and Eurocode 8 have been carried out by means of both push-over analyses and Incremental Dynamic Analyses.

It is useful to underline that this thesis work initially started with the aim of analysing only MRF-EBF dual systems with vertical links (Inverted Y-scheme) which has already led to the publication of some research papers [25], [26], and, only at a later time, moved also to the study of MRF-EBFs dual system with horizontal links (K-scheme, D-scheme and V-scheme).

Inverted Y-scheme is an EBF typology still not sufficiently investigated and not largely widespread despite having many advantages both in term of performance and construction. Its main characteristic is that the link, i.e. the dissipative zone, does not belong to the beam member. In fact, one of the primary benefits in using such structural typology regards the chance to substitute easily the damaged link after a destructive seismic event, and, in addition, the possibility to conceive the scheme within the framework of supplementary energy dissipation strategy, by substituting the vertical link member with a dissipative device, such as a friction damper [41] or hysteretic damper, which is able to exhibit a highly dissipative behaviour if compared with traditional link members. As damaged links can be easily removed and substituted after earthquake, such structural scheme exhibits the greatest advantages provided that the other structural members as beams, diagonals and columns, have been not damaged during the seismic event, i.e. have remained in elastic range. This is precisely why a proper design is of paramount importance. In fact, only with collapse mechanism of global type it is possible to assure that damage is concentrated only in dissipative zones while the other non-dissipative ones remain in elastic range. This important scope is, out of doubts, the strength of the Theory of Plastic Mechanism Control.

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