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VULNERABILITY REDUCTION OF STEEL MOMENT RESISTING FRAMES BY MEANS OF REDUCED BEAM SECTION

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The idea and the developed example of this work are based on the attainment of seismic performance improvement by simply trimming the flanges of the beam-ends. This strategy is to be applied by considering both the results of the theory of plastic mechanism control and the rules assuring the yielding of reduced beam sections (RBS) when seismic loads are applied to the structure. The results of such strategy are not always effective. In fact, there are several conditions that are to be satisfied in order to obtain an actual seismic improvement. Notwithstanding, when these conditions are satisfied, the cost of intervention can be considered as negligible. For this reason, this strategy can be very interesting and the rules applied in this work can clarify which is the effect of RBS taking into account all the parameters playing a role in the final design, i.e. existing column sections, resistance and ductility of existing connections, vertical loads acting in seismic load combination, amount of the reduction of beam section and its distance from the connection.

Keywords: Collapse mechanism, Reduced beam section, Soft story, Dog-bone connection, Failure mode control, Ductile behavior.

1 INTRODUCTION

The first idea of RBS was due to A. Plumier 1990 during a research project financed by the Luxembourg steel producer ARBED and the European Union with the aim of increasing the ductility of the structure by promoting the development of plastic hinges in the beams rather than in the columns. At that time the idea was patented by ARBED, and, due to the reduction of the beam flange width by means of a "dog-bone" shape at a proper distance from the column flange, RBS connections have been also called “dog-bone” connections. In 1994 Northridge earthquake and in 1995 Kobe earthquake a lot of unexpected damages to steel moment-resisting frames were observed. These damages were mainly due to the failure of welded beam-to-column connections. For these reasons ARBED waived any licensing fees and claims and RBS connections started to be investigated by a lot of researchers (Chen *et al.* 1997, Ivankiw *et al.* 1998). Since that time one of the main objective of the research concerning the “dog-bone” connections has been the development of design rules able to promote the beam yielding for safeguarding the beam-to-column connections. So, it can be concluded that structures in high seismicity zones are normally designed to resist severe earthquakes by dissipating the input energy by means of inelastic deformations and, in order to maximize this effect, plastic hinges need to be developed at beam ends rather than in the columns in case of moment resisting frames (MRFs) (Longo *et al.* 2014, Giugliano *et al.* 2010a, Longo *et al.* 2012a, Longo *et al.* 2014, Longo *et al.* 2016, Montuori *et al.*

2012, Montuori and Muscati 2015, Montuori and Muscati 2016, Longo *et al.* 2012b, Montuori *et al.* 2014, Montuori *et al.* 2015a, Tenchini *et al.* 2014). However also in the case of other structural typologies the need to avoid the yielding of columns is always the desired goal and the development of a global mechanism is the main design objective (Castaldo and Tubaldi 2015, Castaldo *et al.* 2015, Colajanni *et al.* 2015, Giugliano *et al.* 2010b, Longo *et al.* 2008a, Longo *et al.* 2008b, Longo *et al.* 2008c, Longo *et al.* 2009a, Longo *et al.* 2009b, Montuori *et al.* 2014a, Montuori *et al.* 2014b, Montuori *et al.* 2014c, Montuori *et al.* 2015b, Montuori *et al.* 2015c). When we have an existing structure designed according to old seismic codes or even with no particular rules for seismic protection the same design objectives above recalled became relevant. In fact, in those cases the structure has been designed with no particular rules for the development of a dissipative collapse mechanism. In addition, the beam to column connections has a very poor dissipative behavior and have no over strength with respect to the beam plastic moment.

2 RBS DESIGN RULES

As it is well known when we need to retrofit a steel structure in order to improve its seismic resistance we can add material to different zones of the structure. In particular we can add steel plate to columns in order to increase their resistance. In this way we can move the plasticization from the column to the beam-ends. But at this point another problem appears: the connections do not have the over-strength which can guarantee the yielding of the beam ends rather than the connections and, in addition, the connections themselves cannot provide the ductility required to assure the development of a dissipative mechanism. In fact, as already mentioned, also in the case of connections designed to resist to seismic action (Kobe and Northridge) the performance exhibited were inadequate due to the brittle failure of the welds. For this reason, also generally, the retrofitting of beam to column connections becomes mandatory. In this context the strategy of reduced beam section can be a very economical solution, because the cut of beam flanges can be considered as a negligible cost. In fact, the realization of "dog-bone" at the ends of each beam could solve both the problem of avoiding a very poor dissipative mechanism and the problem of avoiding the yielding of beam to column connections. In addition, it is important to underline that the weakened beam section is characterized by the decrease, with respect to the original section, of the width-to-thickness ratio of the flanges, i.e. a reduced local slenderness, which leads to the improvement of the plastic rotation capacity. The first problem to be solved is the one concerning the location of RBS is the beam and the amount of the reduction. Regarding this point, we have to apply the results found in (Montuori 2014). If we consider that seismic action can be represented by means of an appropriate distribution of increasing horizontal forces, it is preliminarily necessary to observe the shape of the bending moment diagram of a generic beam subjected to both horizontal forces and vertical loads (Figure 1). We can apply the superposition principle by considering separately the effect of vertical loads and the effect of horizontal forces (Figure 1). Therefore, the resulting bending moment diagram is given in Figure 2, where the sections corresponding to the beam ends (sections 1 and 5), those corresponding to the "dog-bone" locations (section 2 and 4) and that corresponding to the maximum bending moment (section 3) have been pointed out. It is evident that the design parameters are the location of the "dog-bones" (which is denoted with the distance an in Figure 2 and the magnitude of the weakening characterizing the "dog-bones". This second parameter can be expressed in non-dimensional form as $m_{db} = M_{p.db}/M_P$ where $M_{p.db}$ is the plastic moment of the weakened beam section and M_p is the plastic moment of the complete beam section. In this phase of the design procedure the m_{db} value can assumed as fixed, while the location *a* of the "dog-bones" is to be properly selected. It is important to note that at the left side of the beam (beam sections 1 and 2) the bending moments due to vertical loads and horizontal forces have an opposite sign (one is anti-clock-wise and another is clock-wise), while at the right side (beam sections 3 and 4) they have the same sign (clock-wise). Due to this consideration, it is obvious that for increasing values of horizontal forces the first plastic hinge develops in beam section 4 or 5 rather than in beam section 1 or 2. Conditions able to locate the plasticization in both dog bones on in the left dog bone and in section of maximum bending moment 3 have been found and analyzed in (Montuori 2014) leading to obtain a design abacus for the dog-bones.

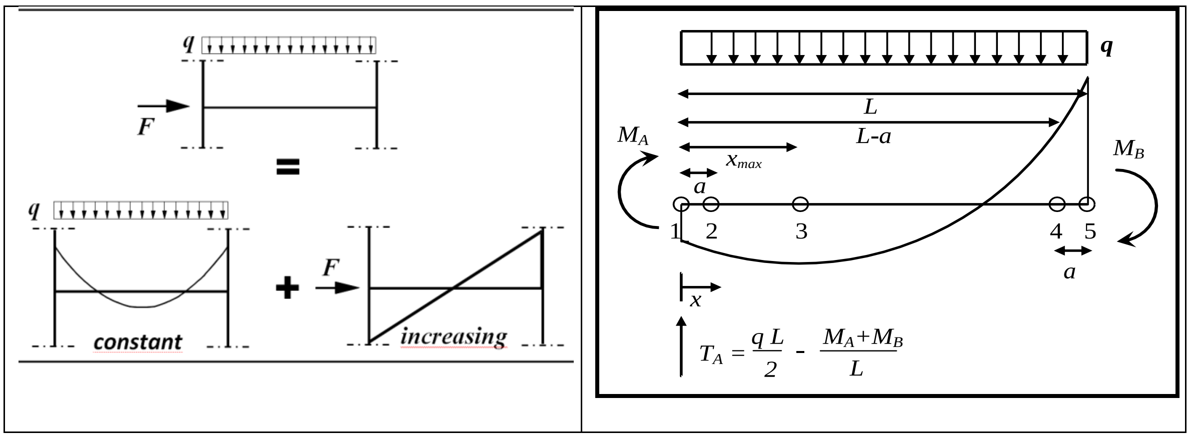

Figure 1. Bending moment due to vertical and seismic loads.

3 APPLICATION OF THE THEORY OF PLASTIC MECHANISM CONTROL

The theory of plastic mechanism control (TPMC) has been developed, applied and verified for a lot of structural typology. In this case it is applied for the evaluation of the effectiveness of the RBS. In fact, by using the results of such theory we can determine the conditions assuring the development of a collapse mechanism better than the original one, in particular we can understand if the soft story mechanism (when this is the collapse mechanism of the original structure) can be avoided or not by simply trimming the beam flanges. TPMC procedure is based on the kinematic theorem of plastic collapse and on the concept of mechanism equilibrium curve.

In particular, it is observed that the collapse mechanism of a frame subjected to horizontal forces can belong to three collapse mechanism typologies (Montuori *et al*. 2015a), so that the failure mode control can be obtained by analyzing $3n_s$ collapse mechanisms, being n_s the number of stories. Moreover, the design procedure accounts for the influence of second order effects by extending the kinematic theorem of plastic collapse to the concept of mechanism equilibrium curve. In fact, the plastic moments of the columns are derived by imposing that, within a given displacement range depending on the plastic rotation supply of members and connections, the mechanism equilibrium curve corresponding to the global mechanism has to lie below the mechanism equilibrium curves corresponding to all the remaining 3ns-1 kinematically admissible mechanisms. It is important to underline that, for any given geometry of the structural system, the slope of mechanism equilibrium curve attains its minimum value when the global type mechanism is developed. This issue assumes a paramount importance in TPMC exploiting the extension of the kinematic theorem of plastic collapse to the concept of mechanism equilibrium curve. In fact, according to the kinematic theorem of plastic collapse, extended to the concept of mechanism equilibrium curve, the design conditions to be fulfilled in order to avoid all the undesired collapse mechanisms require that the mechanism equilibrium curve corresponding to the global mechanism has to be located below those corresponding to all the undesired mechanisms within a top sway displacement range, δ_u, compatible with the ductility supply of structural members.

The conditions to avoid undesired mechanisms can be found in Montuori *et al*. 2015a.

$$\alpha_0^{(g)} - \gamma^{(g)}\delta_u \leq \alpha_{i_m}^{(t)} - \gamma_{i_m}^{(t)}\delta_u \quad for \qquad i_m = 1,2,3,\dots,n_s \quad t = 1,2,3 \tag{1}$$

4 STUDY CASE

In order to show the effectiveness of the proposed procedure we can consider the structure depicted in Figure 2. It was designed according to the Old Italian seismic code (DM96). By means of a simply push over analysis, made with Sap2000 computer program, it shows a great vulnerability to seismic action.

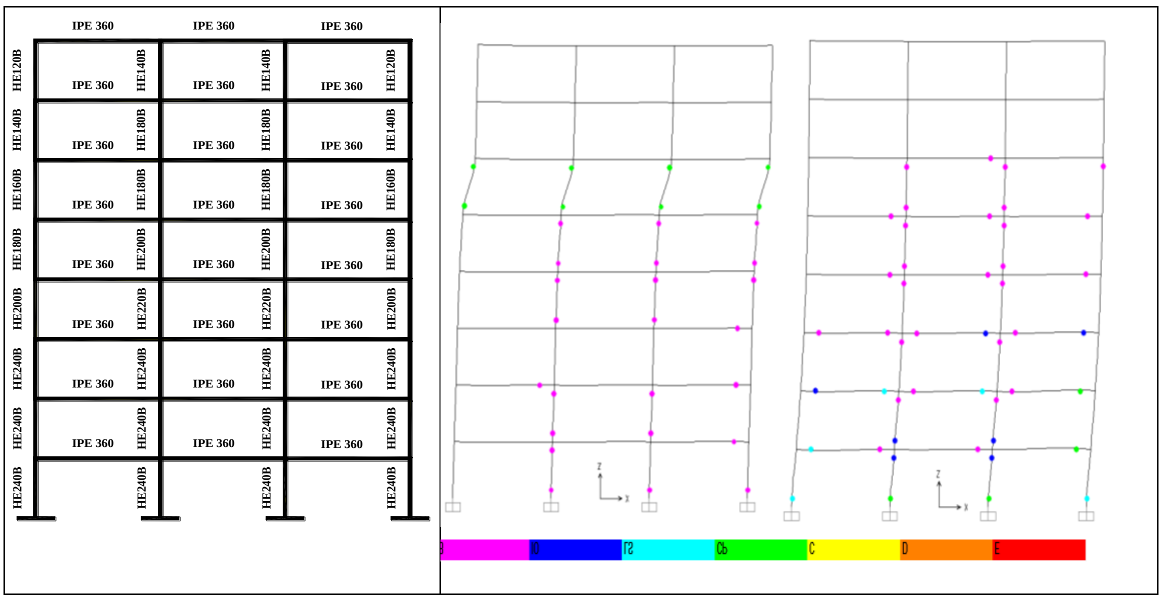

Figure 2. The analyzed structure with soft story mechanism developed by the existing structure (left side) and the mechanism developed by structure with dog bones (right side).

In fact, as represented in Figure 2, a soft story mechanism develops. By applying the proposed procedure, it is easy to recognize that a weakening of all the beams can be realized. The maximum amount of the section reduction, which allows verifying the entire serviceability requirement, is equal to 0.7 M_p. If we assume an available ductility of columns equal to 0.04 rad, then the value of the top sway displacement δ_u can be determined. With the aim to verify this conclusion another push over analysis has been made on the structure with dog bones. The result of the push over is reported in Figure 2. From this figure we can observe that a soft story has been avoided and, in addition, a consistent number of beams have been significantly involved in the collapse mechanism. In fact, the green color shows that both the two of the first story columns and two dog bones have achieved a plastic rotation of 0.04 rad which is the value assumed as the maximum admissible value both for beams and columns. On the contrary in the existing structure only few beams are involved in the collapse mechanism, but their contribution to the dissipation is very low. In fact, in Figure 2 the color of yielded beams indicates that the rotation is less than 1%. The analyses have been stopped when the available ductility (0.04 rad) has been achieved at least in one element. It is evident a greater ductility available for the structure with dog bones. Finally, in order to have a further confirmation of the effectiveness of the proposed procedure, also non-linear dynamic analyses have been carried out. In particular, the three real earthquakes reported in Table 1 have been considered. From these analyses the differences in seismic behavior are actually significant. Analyses have been repeated by progressively increasing the multiplier of the earthquake. For each structure and for each considered earthquake the value of the multiplier corresponding to the attainment of a rotation greater than 0.04 rad has been determined.

Table 1. Percent increase of PGA carried by structure with dog bones with respect to original structure.

Earthquake	Connections ductility (0.04 rad)	Connections ductility (0.02 rad)
Northridge	14%	14%
Imperial V.	9.5%	50%
Santa Barbara	21%	28%

Finally this value has been compared and an increase in seismic performance for the structure with dog bones of 14%, 9.5%, and 21% for Northridge, Imperial Valley and Santa Barbara, respectively, has been found (Table 1). In addition, if we consider then in the existing structure the hinges develop in the connections, a bigger increment in seismic behavior is obtained. In fact, assuming that the limit ductility of connections is equal to 0.02 rad the increase can be of 50% for the Imperial Valley earthquake as reported in Table 1. So it can be concluded that a significant seismic improvement has been achieved by simply trimming the flanges of the beams. Obviously further improvement can be obtained by increasing same column sections according to the condition s to avoid Type 1, Type 2, and Type 3 mechanisms reported in Montuori *et al*. 2015a.

5 CONCLUSIONS

In the present paper the problem of strengthening a steel moment resisting frame in seismic zone has been considered. The idea and the developed example of this work are based on the attainment of improvement of seismic performance by simply trimming the flanges of the beam-ends. An example of significant seismic improvement has been showed. The strategy can be very interesting because it requires no additional materials and the cost to cut the beams is really negligible if compared with the obtainable results. It is important to underline that this methodology is not always effective. In fact in some cases the introduction of dog bones can determine a negligible seismic improvement due to the development of a soft story mechanism, which could be avoided only by means of an increase of some column sections.

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