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RELIABILITY OF JOINT SYSTEMS FOR IMPROVING THE DUCTILITY OF MR-FRAMES

A.Anastasiadis[1], G. Mateescu[2], V.Gioncu[1], F.M. Mazzolani[3]

[1]Politehnica University Timisoara, 1900 Timisoara, Str T.Lalescu 2, Romania
[2] INCERC Timisoara, 1900 Timisoara, Str. T. Lalescu 2, Romania
[3] University of Naples ‘Federico II’, Italy

ABSTRACT

Two important issues regarding steel moment resisting frames (MRFs) are investigated in this paper. Firstly, a parametrical study was conducted on local ductility of new joint types resulted by the beam section reduction or by the beam-to-column joint strengthening, using DUCTROT’96 computer program. The second part deals with the inelastic global performance of different MRFs types subjected to some scaled ground motions. Using Drain-2D computer program, ductility requirements were determined. The numerical results indicate that the proposed modified MRFs could be an effective solution for controlling structural response, but in some specific cases the new solutions must be used with caution.

KEYWORDS

Moment resisting frames (MRFs), Reliability of joint details, Plastic rotation capacity, Inelastic global analysis, Earthquake , Ductility.

INTRODUCTION

Steel moment resisting frames are the most popular structural system in many high seismicity areas for several reasons. Firstly, moment resisting frames (MRFs) are considered as highly dissipative systems. Secondly, moment resisting frames are widely used because of their simplicity in execution, as well as due to their architectural versatility.

During the last severe earthquakes (Michoacan, 1985, Loma Prieta, 1989, Northridge, 1994, Kobe, 1995), many modern steel moment resisting frames were seriously damaged, challenging the assumption of high ductile systems. However, evidence of global structural collapses has been reported in few occasions only (for instance Pino Suarez Building, Mexico, 1985).The main lessons learned from the recent earthquake events (Northridge and Kobe) are related to the important differences between the characteristics of earthquakes recorded at different distances from the source (near field vs. far field), as well as the incomplete understanding of the inelastic behaviour of beam-to-column joints in moment resisting frames (Gioncu & Mazzolani, 1999). Unprecedented cases of brittle and unpredicted failure of welded-flanges-bolted-web connections were identified in rigid frames, designed as special (ductile) moment-resisting frames. In all cases there was little, or no evidence, that plastic hinges had developed in the beams prior to weld fractures. As a consequence, a variety of ideas for improving the joint inelastic behaviour by reducing the beam section or by strengthening the joint, were proposed (Plumier, 1996, Chen et al, 1997, SAC, 1995). In the case of frames, recent investigations confirmed that the beam-to-column joints have fundamental importance in seismic response, because dissipative zones have to be located at the beam ends, and that their rotational ductility supply is strictly dependent to the detailing of connections (Mazzolani, 1998). In this way, inelastic behaviour, dynamic characteristics, natural period and influence of superior modes, must be evaluated related to different site ground motions, for ensuring the reliability of the chosen joint details.

The subject of the present paper is focused on two main aspects: the local performance of the joint details, resulted by weakening the beam section or strengthening the joint, and the effectiveness of the overall seismic behavior of a modified moment-resisting frame, as compared with the special and ordinary frames, for different characteristic earthquakes. Using the structural analysis package Drain-2D, global ductility requirements were evaluated, while for determining the available local ductility, the DUCTROT'96 computer program was used.

LOCAL PERFORMANCE OF THE MODIFIED MOMENT RESISTING JOINTS

For determining the local available plastic rotation, $\theta_{p.av}$, a proper methodology based on the local plastic mechanism and the 'standard beam concept' was used (Gioncu & Petcu, 1997). A computer program DUCTROT'96 has been elaborated at INCERC Timisoara (Gioncu & Petcu,1996) for evaluation of the ductility of local plastic mechanism (Fig.1). Based on the high number of theoretical and experimental data, the available plastic rotation is proposed to be determined by the following relation which corrects the values obtained by DUCTROT'96, taking into account some factors affecting local ductility (Anastasiadis, 1999):

$$\theta_{P.av} = c_r \frac{r_w r_s}{\gamma_M} \theta_{P.u} \tag{1}$$

where:

- $\theta_{p.av}$ - available plastic rotation capacity;
- $\theta_{p\cdot u}$ - ultimate plastic rotation capacity determined using DUCTROT'96;
- c_r - coefficient taking into account the influence of junction between flange-web in case of hot rolled section (1.63...1.76 for IPE profiles and for HE profiles);
- r_w - coefficient taking into account the influence of incomplete mechanism, ($r_w \approx 0.75\ldots0.50$);
- r_s - coefficient taking into account the cyclic seismic action as a function of flange slenderness.

Local ductility of reduced-beam section (Dog-bone solution)

During severe earthquakes, great moment capacity demands are developed at the face of column, producing high stress concentrations in this region. When a cross section of the beam near to the beam-to-column interface is reduced at a selected location, having a smaller moment capacity than required, the first plastic hinge would form at that location, away from the column face, protecting the joint wedings. A reduced beam section illustrating the main geometrical parameters, as well as the concept of sizing such sections is presented in Figure 2a. The influence of geometrical characteristics on the beam ductility is plotted in Figure 3.

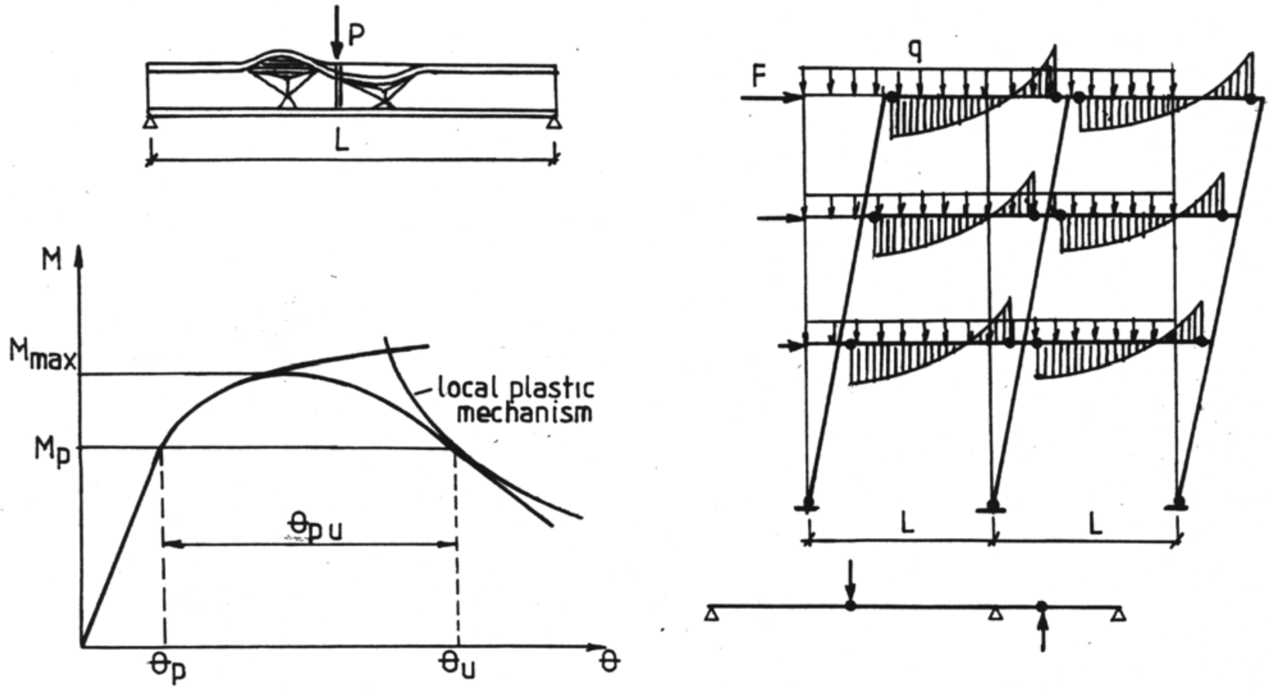
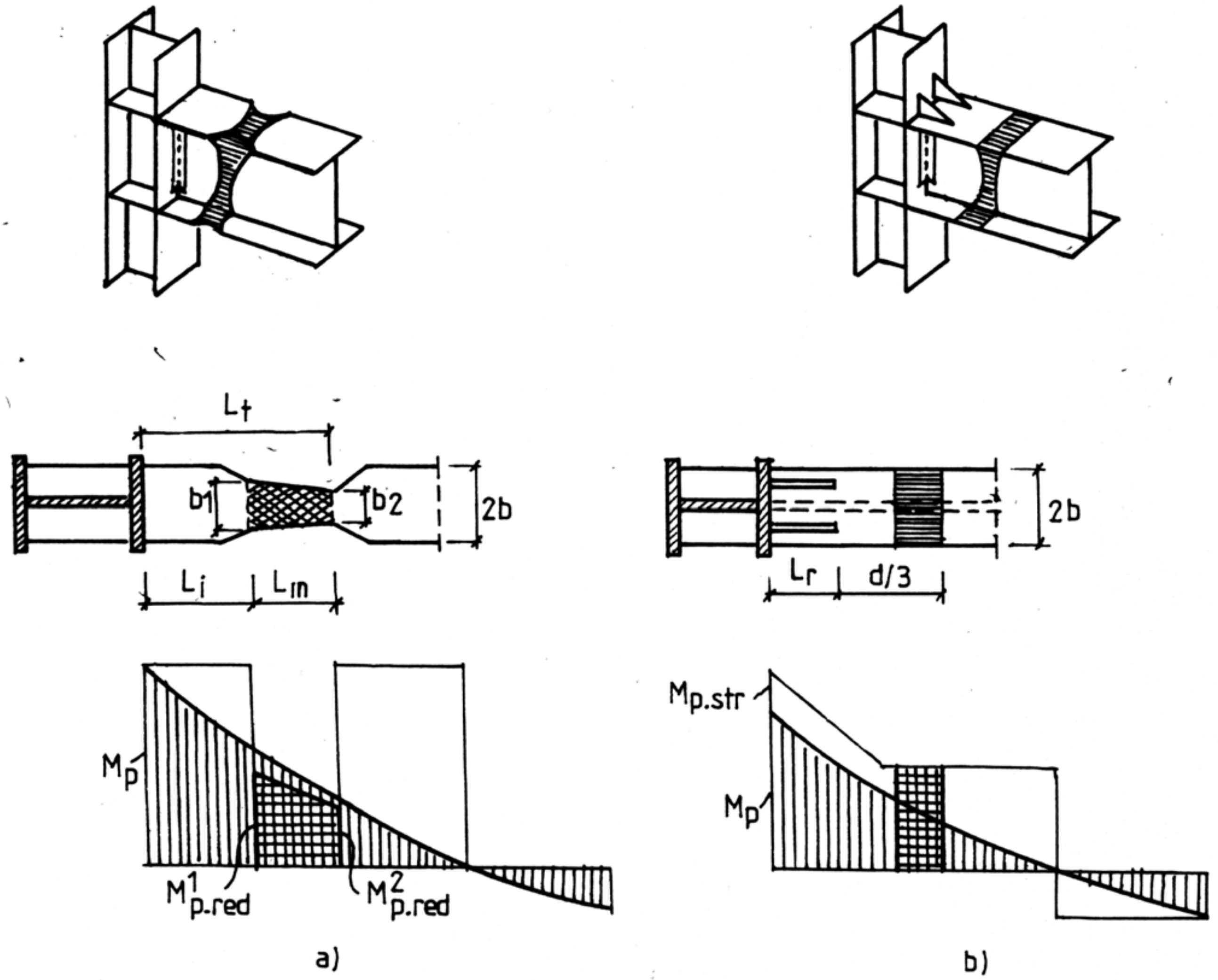


Figure 1: Determination of available plastic rotation capacity



a)

b)

Figure 2: Analysed moment joints

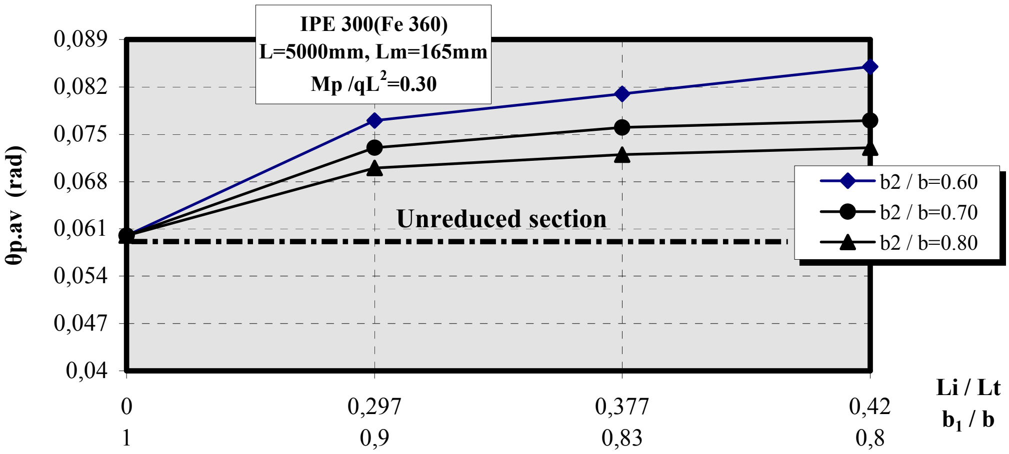


Figure 3: Influence of geometrical parameters

High plastic rotation capacities can be achieved in the case of 'dog-bone' solution. When beam flange reduction is about 40%, an increasing with 37% of rotation capacity can be obtained , as compared with the normal unreduced beam section. It is very important to consider in analysis the influence of gravitational loads, otherwise the above mentioned effect of weakening could be questionable (Fig.4). A more comprehensive parametrical study about the factors influencing the local ductility of dog-bone solution is given by Anastasiadis & Gioncu (1998).

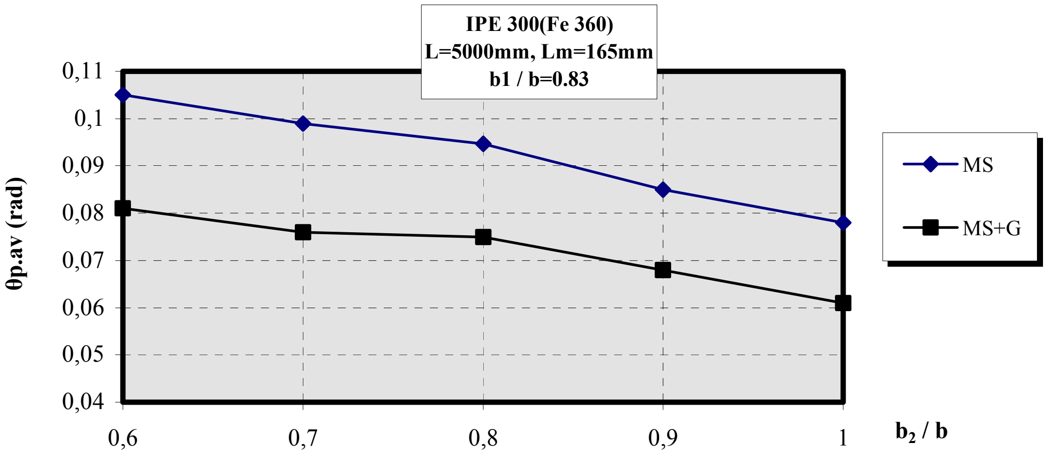


Figure 4: Influence of gravitational loads

Ductility of reinforced beam section

A second solution for improving ductility of moment-resisting joints is the application of different joint strengthening schemes, using ribs, haunches, cover plates, side plates, etc. (SAC, 1995). The dimensions of strengthened beam with ribs are presented in Figure 2b. The influence of ribs length and the plastic hinges position on the plastic available rotation capacity is plotted in Figure 5. One can see an increasing of this capacity of about 8%, comparing with the unreinforced beam section. Experimental evidence shows that for these type of strengthening the plastic hinge occurs at the distance d / 3 from the edge of the reinforced connection. From Figure 5 it can be observed that relocating the plastic hinge away from the ribs end, an additional rotation capacity can be achieved, of about 4%, as compared with the situation when plastic hinge is formed exactly at the edge of the rib. One can see that the reinforced beam section is less effective than the dog-bone solution.

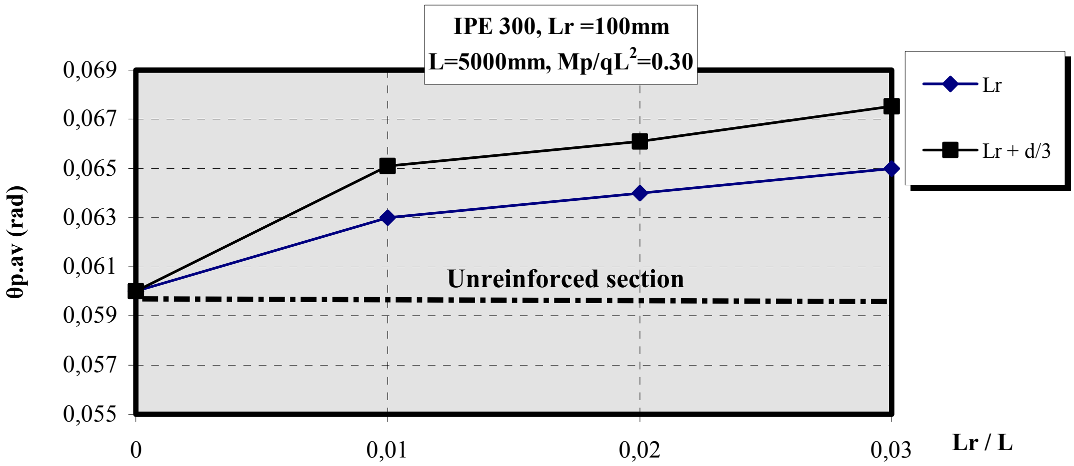


Figure 5: Influence of rib length

GLOBAL PERFORMANCE OF DIFFERENT MRFs TYPES

Considerations of the parametrical study

The parametrical study is developed for 3 stories - 2 bay frames, as a function of the inelastic behaviour demands due to the different conformation of the frames. Special moment-resisting frames, SMRF, ordinary moment-resisting frames, OMRF, as well as modified moment-resisting frames, the dog-bone frame, DBF, and reinforced frames, RF, were investigated. The geometry of frames and the gravitational loads are presented in Figure 6a. SMRF is sized to form a global mechanism, having HE-280B columns and IPE 300 beams, while OMRF is dimensioned to develop a storey mechanism, having HE-240B columns and IPE 300 beams (Fig.6b). The DBF and RF are based on the OMRFs general dimensions, intending to transform them in special moment-resisting frames (Fig.6c,d), using dog-bone or reinforced solutions.

All the frames were subjected to main Romanian earthquakes, Vrancea (1977) and Banat (1991) and also to Kobe earthquake (1995). Each of these ground motions introduce different aspects concerning the structural response. The Vrancea earthquake is a typical far-field earthquake, while Kobe and Banat earthquakes are specific near-field ones, with velocity impulse characteristics. The difference between them is that the Kobe earthquake has more velocity pulses, while the Banat earthquake has a single velocity pulse only. The effectiveness and the reliability of the above solutions were studied, normalizing the proposed accelerograms at 0.35g, 0.25g, 0.15g, considered as high, moderate and low seismic accelerations (Mazzolani & Piluso, 1996) (Table 1).

The numerical modeling of the modified frames, DBF, RF, was made by using the beam-to-column element from the Drain-2D computer program, introducing rigid or weakened short elements and fictive bearings as showed in Figure 6e,f.

Analysis of the results

Studying the results of the parametrical analysis, the following main findings should be emphasized:

TABLE 1
NORMALIZED GROUND ACCELERATIONS

Ground motion	P.G.A a_0 (g)	Scaling factor, λ	Normalized acceleration (g)	Scaling factor λ	Normalized acceleration	Scaling factor, λ	Normalized acceleration
Vrancea INCERC 1977	0.199	1.60	0.35	1.14	0.25	0.682	0.15
Banat Long 1991	0.03	11.6		8.33		5.0	
Kobe 1994	0.296	1.18		0.85		0.506	

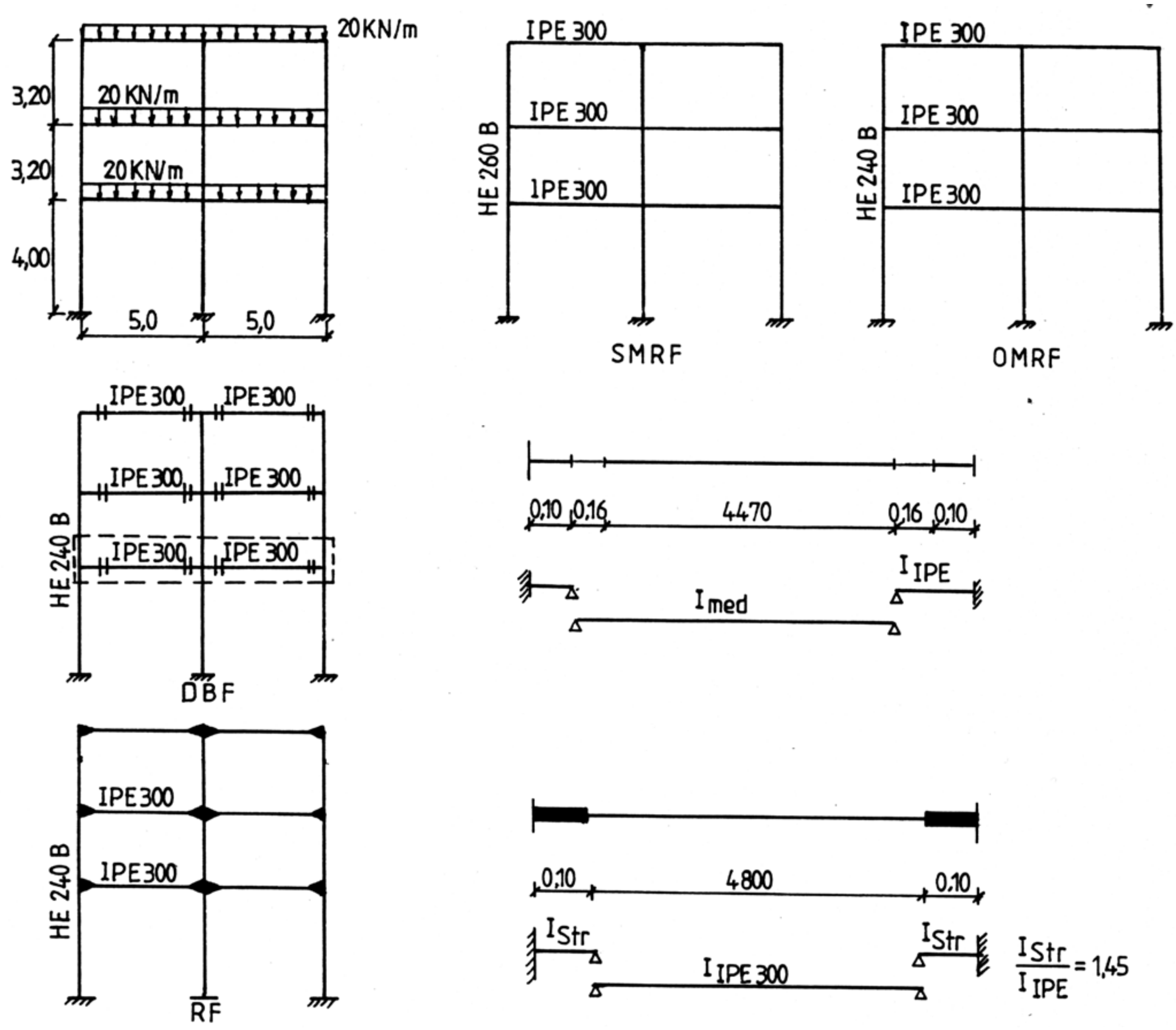


Figure 6: Geometry and modeling of examined types of frames

- For low seismic ground motions, 0.15g, the inelastic behaviour requirements were not so significant, all the frame types sustain the ductility demands, while for Banat earthquake the structures does not enter in plastic domain.
- In case of far-field ground motion (Vrancea), Fig.7,8, medium ductility requirements for both strong and moderate seismic actions were marked. Modified moment-resisting frames, DBF, RF, as well as SMRF undergo these inelastic requirements, forming plastic hinges only at the beam ends, while OMRF develops plastic hinges both at beams and columns, having a prone inelastic behaviour for life safety.
- In case of near-field ground motion (Kobe), Fig.8,9, high ductility requirements were marked. One can see that OMRF and SMRF do not satisfy the ductility requirements for high and moderate earthquakes, the first one forming a storey mechanism as expected. In exchange the modified moment-resisting frames, DBF, RF, concentrating the plastic hinge away from the column face, have sufficient available plastic rotation capacities, forming a global mechanism.
- In case of local Banat earthquake (Fig.8.10), some new specific characteristics were observed. For high and moderate accelerations, 0.35g, 0.25g, respectively, the ductility demand was minor, because other earthquake parameters than peak ground acceleration, have influence on the structure behaviour. Completely different inelastic behaviour was find as compared with the Kobe earthquake due to the presence of a single velocity pulse. While SMRF has a good global performance, modified moment-resisting frames can be ineffective for this earthquake type (Fig. 9,10).

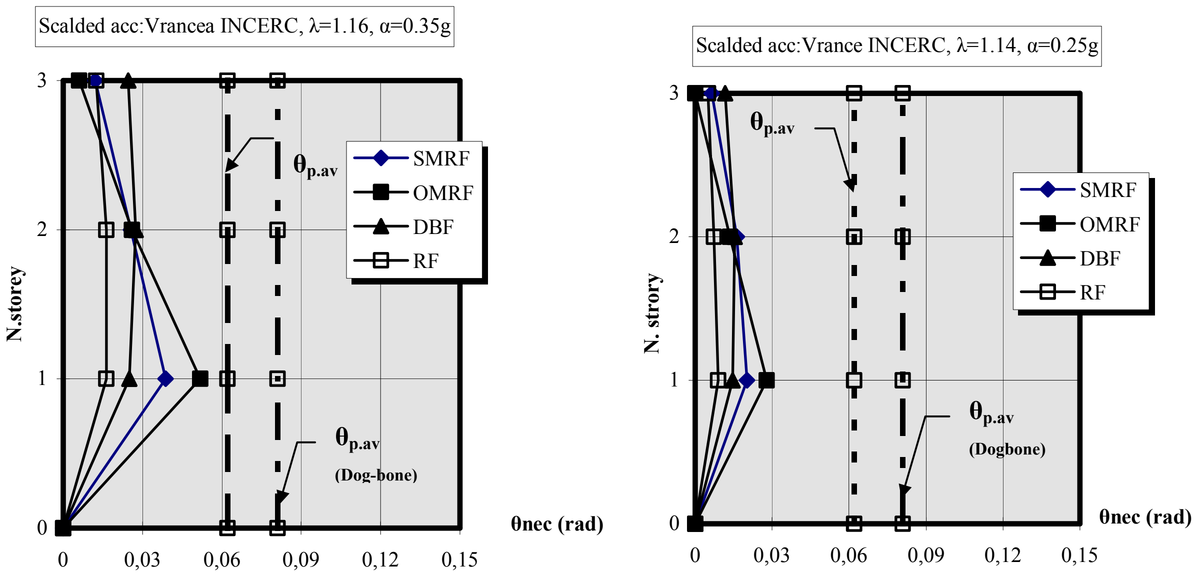


Figure 7: Ductility demands for the normalized Vrancea earthquake

From the local point of view, the moment time history demands of the beam-to-column interface, at the first storey of SMRFs, DBFs and RFs, are shown in Figure 11. One can see the small requirements of moment at the case of DBF, RF, avoiding stress concentration at the weldments. From the global point of view, taking into account the shear index, $V_{m.}$ / V_p (ratio between shear force obtained for 0.35g peak acceleration to storey shear at the first plastic yield), it is clearly showed the superior overall seismic performance of the modified frames. RFs have a little bit better global performance as compared with the DBF, due to smaller inelastic deformations, causing smaller rotation demands. In some specific cases (see Banat earthquake) the use of such joint details could be unreliable.

It is concluded from the parametrical study that, in many cases, the modified moment-resisting frames using dog-bone or reinforced solutions represent attractive solutions to satisfy ductility demand, as well as to mitigate the brittle failures observed in recent earthquakes. In the same time, the case of Banat earthquake shows that these solutions are not universally valuable, depending to the seismicity site characteristics.

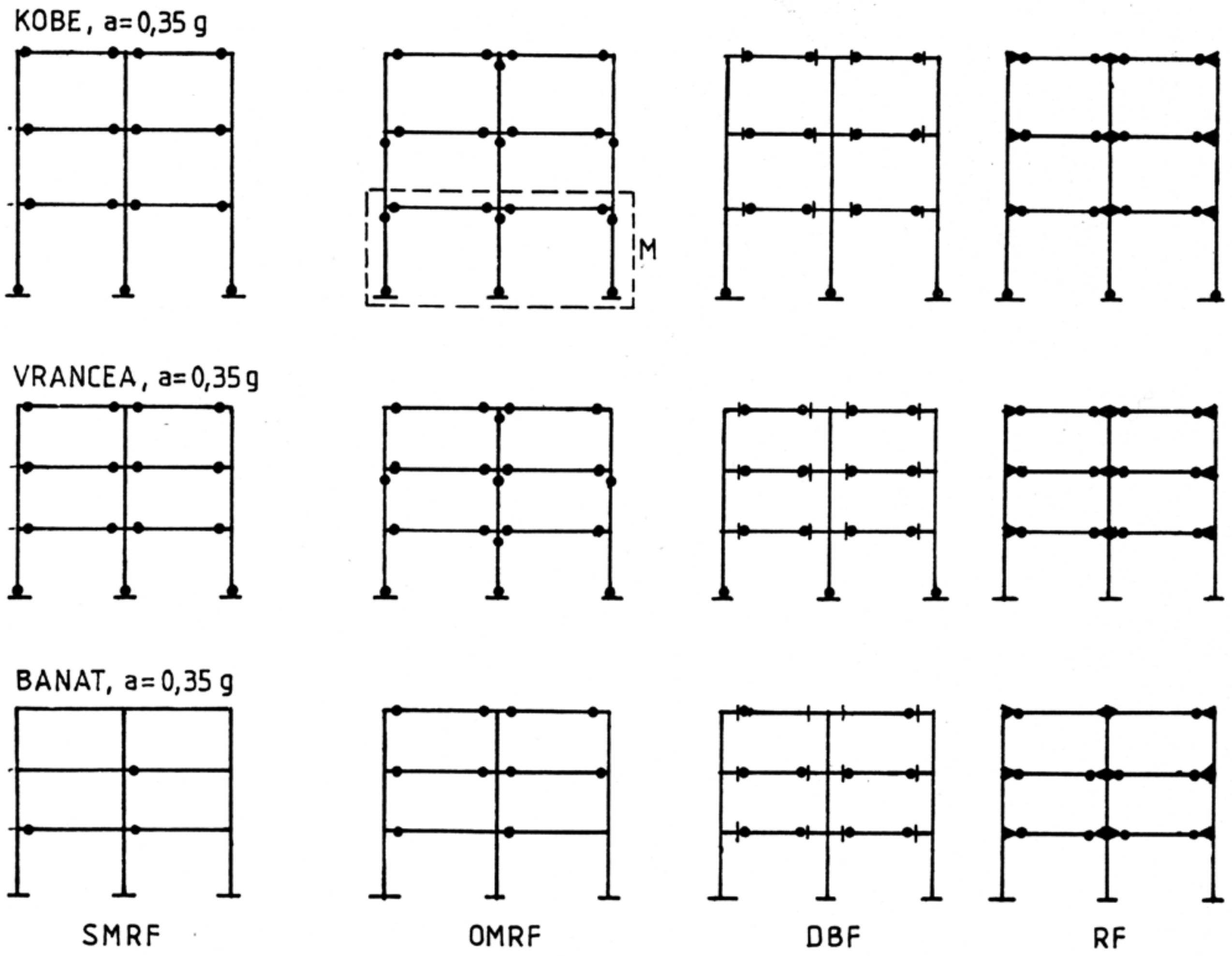


Figure 8: Plastic collapse mechanisms

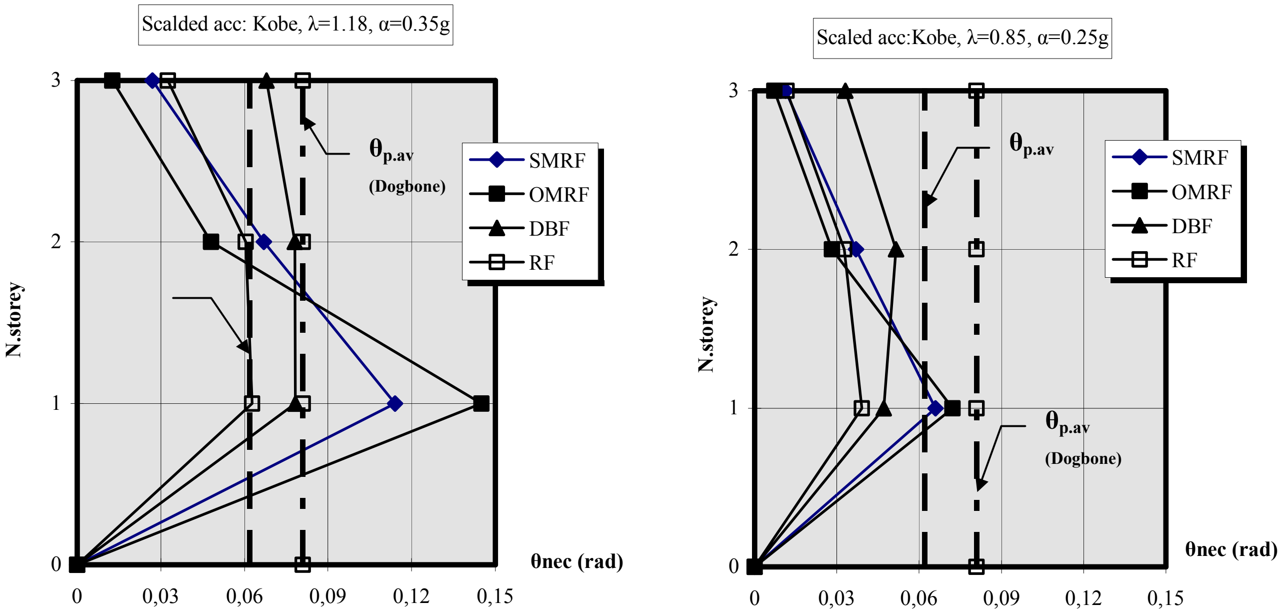


Figure 9: Ductility demands for the normalized Kobe eartquake

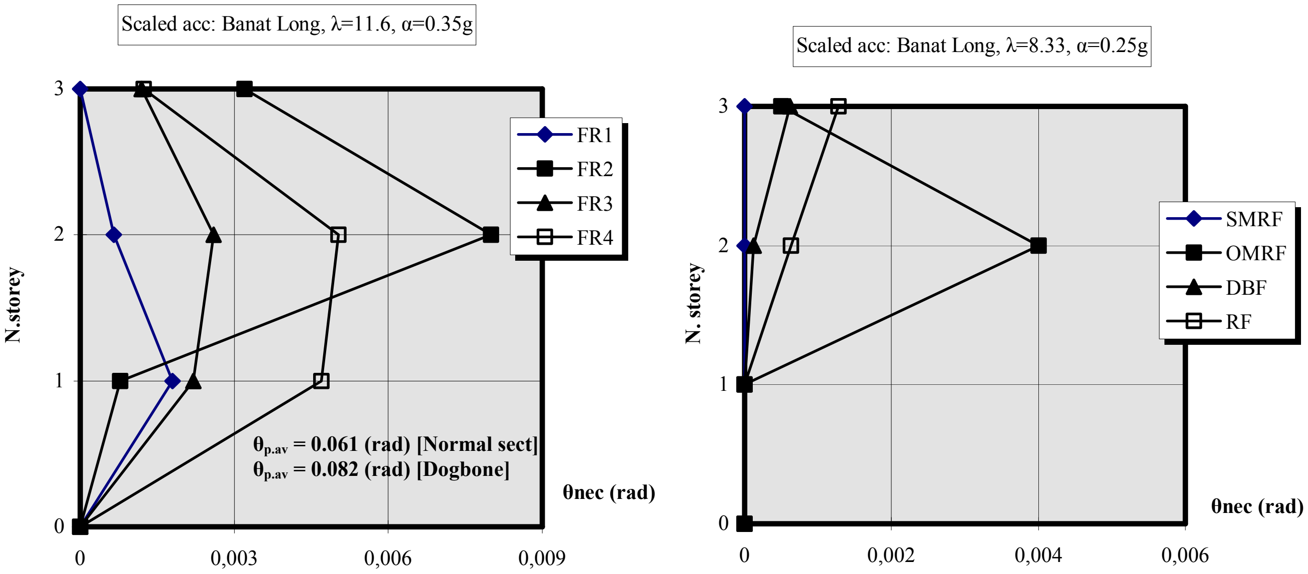


Figure 10: Ductility demands for normalized Banat earthquake

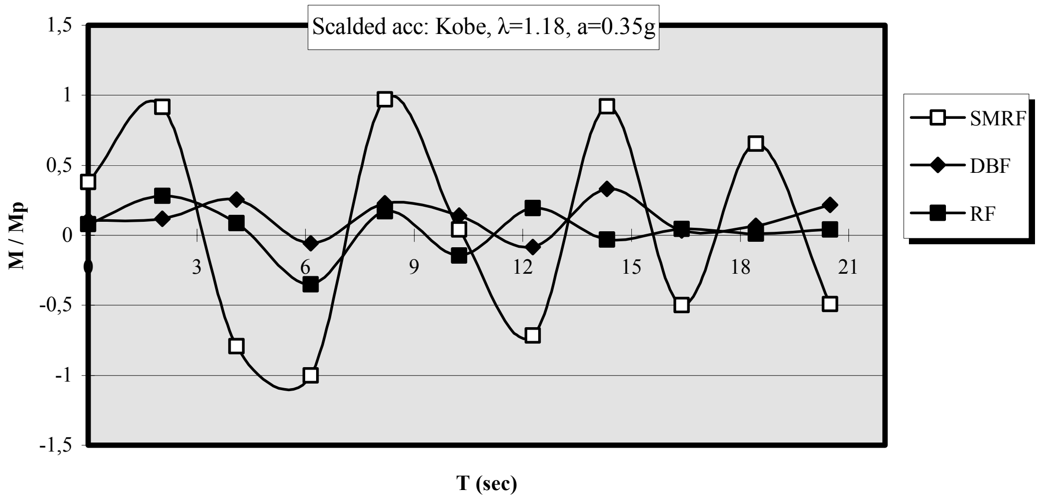


Figure 11: Time history moment demands at beam-to-column interface of the first storey

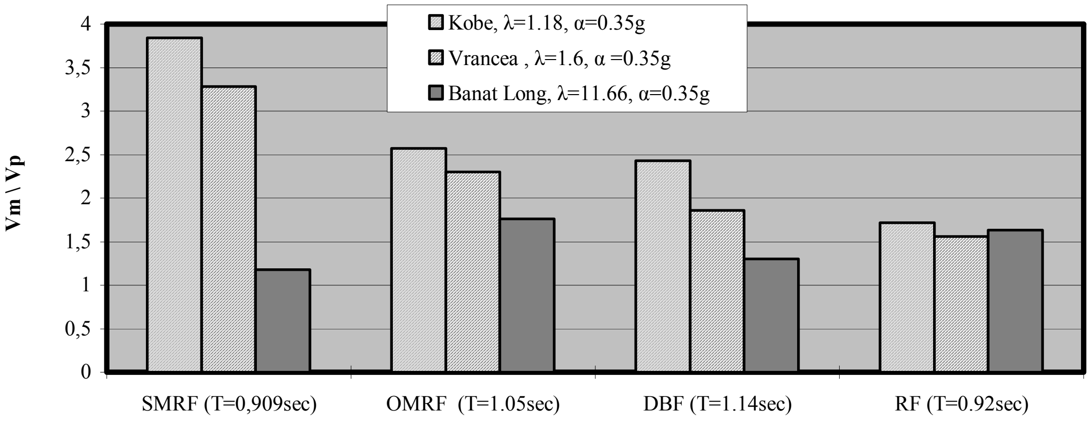


Figure 12: Shear base index of effectiveness

CONCLUSIONS

Analytical investigations were performed on both local and global performance of different moment-resisting frame typologies, using DUCTROT'96 and Drain-2D computer programs. The study concluds that the modified moment-resisting frames, DBF, RF, can help to control the seismic response avoiding the formation of undesirable collapse mechanisms, as storey mechanism. In the same time, these solutions transform OMRFs, in ductile moment-resisting frames, obtaining a predetermined failure mode and the ductility control through concentrated rotation requirements only at the beams, far from joints. In some cases this effect seems to be unreliable; in this way it is need to consider the specific seismicity of the site. Further research work are planned to lighten these aspects.

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