Hybrid Moment Frame Joints Subjected to Seismic Type Loading

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SUMMARY:
Special hybrid moment frame and modified hybrid joints subjected to seismic type loading, test results are discussed. Tested joints are composed of discretely precast concrete column and beams, post-tensioned assembled by unbonded anchor to anchor tendons and non-prestressed connection reinforcement partially unbonded at beam column interface.
Special hybrid moment frame joint respects the provision of ACI T1.2-03 standard. For the modified joint, the difference from the standard one is that both prestressed and non-prestressed are unbonded "anchor to anchor".
The case study analyzes the behavior of an internal joint under lateral loading, based on an actual six storey frame structure, in a high seismicity location. Tested models represent a joint extended up to mid-span of adjacent members. Tests were carried out at imposed displacements, alternative cycles, up to a story drift of 0.025h. Main results and principal conclusions are revealed. For the modified special hybrid joint, design equations are proposed.

Keywords: hybrid joint, precast, post-tensioning, drift, test

1. INTRODUCTION

Moment frame RC structures under seismic loadings have been studied both experimental and theoretical and their results were revealed in numerous technical papers and scientific books, and are reflected by of European and American the building codes provisions.

Taking into account the approach involving the sustainability concept for building development, in last 2 decades, a different concept of seismic design was introduced, based on limit displacements has been gaining confidence as it has become appreciated that structural damage can be directly related to strain (and hence by integration to displacement), and non-structural damage, in buildings can be related to drift. Different approaches have been proposed to increase the emphasis on displacement, one of them being the direct displacement-based seismic design (Priestley, 2007) developed as a simple method for designing to achieve displacement limits that could be strain-based or code drift-limit based. Further more a new concept for design and detailing for RC precast frame structures, located in high seismicity regions is already permitted by US building code (ACI T1.2-03, 2010). The seismic resistant frame is compound of precast beams that are post-tensioned to concrete columns. The precast or cast-in-place columns are continuous through the joints. The beams span a single bay.

These frames are called hybrid frames due to the facts that they combine, on one hand, the post-tensioned and RC members, and on the other hand, the use of ordinary reinforcement designed to yield with prestressed tendons designed to remain elastic during an earthquake. The ordinary reinforcement, called special reinforcement, is placed at the top and the bottom of the beams, and passing through the interface and the columns. Special reinforcement is debonded on a limited length in the beam close to the column-beam interface.

These frames, under seismic loading, are intended to behave differently from the "traditional frames". Most of their deformations occur due to the opening and closing of the column-beam joints at the interface between the precast beams and the columns thus the members displacement are rigid body type. Thus, the damages are practically limited in extend around the joint area. Proper detailing assures, due to the post-tensioned strands designed to remain elastic during the expected seismic event, the return of the frame to its undeformed (initial) configuration, after the event.

Following the new concepts up-mentioned, a different detailing of the hybrid joints was proposed. The main difference consists in replacement of the special reinforcement with ties, resulting both prestressed and ordinary reinforcement unbonded "anchor to anchor". The new detailing is called modified hybrid joint.

2. DETAILING OF THE MODIFIED HYBRID JOINTS

The modified hybrid joint respects the requirements of special hybrid moment frames provisions except for the provisions concerning special reinforcement.

The special reinforcement is replaced by ties made out of ductile steel, 16mm diameter, fixed with screws at the enlarged ends of the beams. They are processed as shown in Fig. 1 and Fig 2.

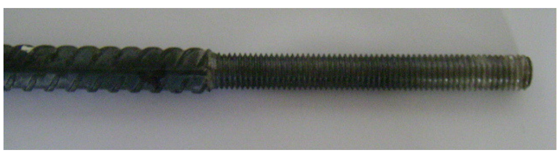

Figure 1. Threaded end M14

Figure 2. Processed zone $\phi 12$

This processing assures that the post elastic behavior occurs in the desired location of the bars and not in their threaded ends.

3. EXPERIMENTAL PROGRAM

Experimental specimens are joints of an actual structure, of 6 stories with 3m height, having a rectangular shape with 3 even spans and 5 equal bays. The overall plane dimensions are 3x6m/5x4m. The location is characterized by a ground acceleration $a_g = 0.24g$.

The seismic action on the structure was determined using the direct displacement-based seismic design method. The single dynamic degree of freedom equivalent structure characteristics are calculated considering that the allowable story drift is 0.025, according to the Romanian seismic code (P 100:1, 2006) and is equal to the first story drift.

Table 1. Ductility characteristics of the equivalent structure

Δ_d	H_e	θ_y	Δ_y	μ
[m]	[m]	[-]	[m]	[-]
0.263	12.576	0.006	0.075	3.489

The displacement spectrum (Fig. 4) is obtained from the acceleration spectrum provided by the Romanian seismic design code (P 100:1, 2006), presented in Fig. 3.

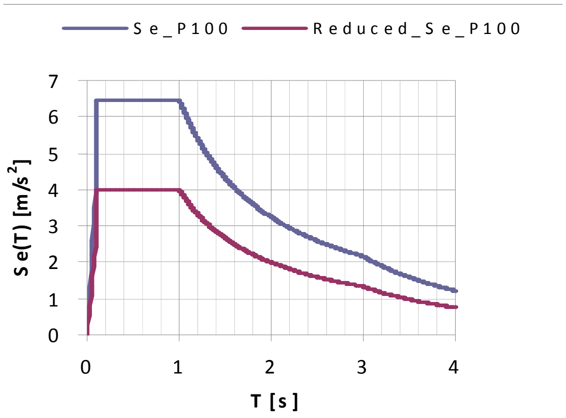

Figure 3. Acceleration spectrum (m/s^2)

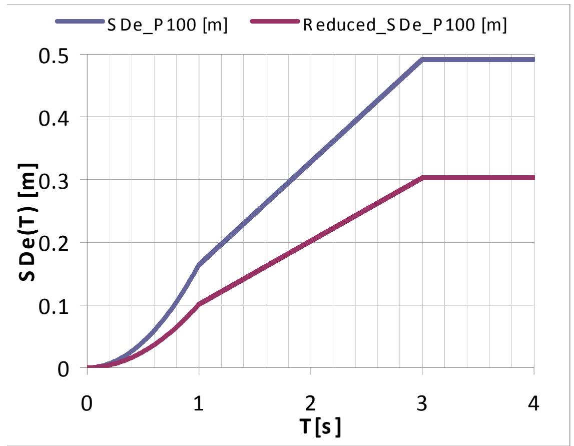

Figure 4. Displacement spectrum

For determining the vibration period the reduced displacement spectrum is used, considering both elastic and hysteretic damp.

The vibration period for the equivalent structure is determined graphically from Fig. 3, considering the reduced displacement diagram.

The design values are presented in Table 2.

Table 2. Design characteristics of the equivalent structure

Vibration period	Secant rigidity	Base shear force
$\mathbf{T_e}$ (s)	$\mathbf{K_e}$ (kN/m)	$\mathbf{V_{base}}$ (kN)
2.5	1421	374

The actual structure was designed considering the above values of the base shear force.

The experimental models were reinforced same as the members of the actual structure. The main characteristics of the model are given in Table 3.

Table 3. Material characteristics of the experimental models

Concrete		Ordinary steel		Prestressing steel			
$f_{ck,cube}$	E_{cm}	R_m (f_u)	A_5	F_{po1}	F_m	A_{gt}	E
(MPa)	(MPa)	(MPa)	%	(kN)	(kN)	%	(MPa)
34.1	31000	570	25	159.6	178.0	5	189700

The test models represent the internal connection at the first storey of the actual building, extended up to mid span of the adjacent members.

General view and reinforcement set-up of the experimental specimens is presented in Fig. 5.

Connections detailing of the of hybrid joint model (N1) and of the modified hybrid joint model (N2) are presented in Fig. 6 and respectively in Fig. 7.

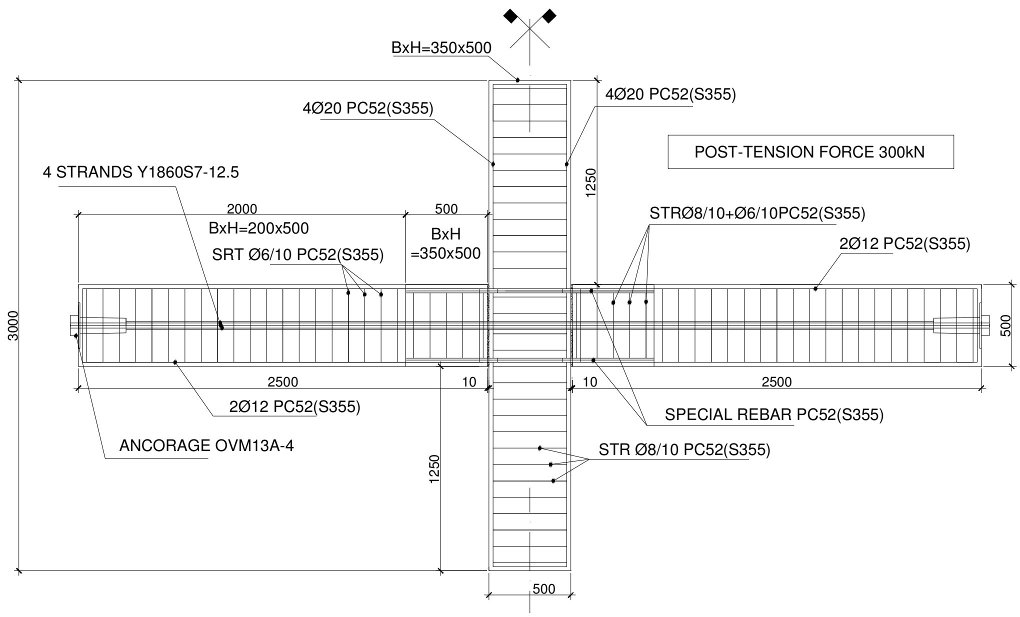

Figure 5. Test specimens

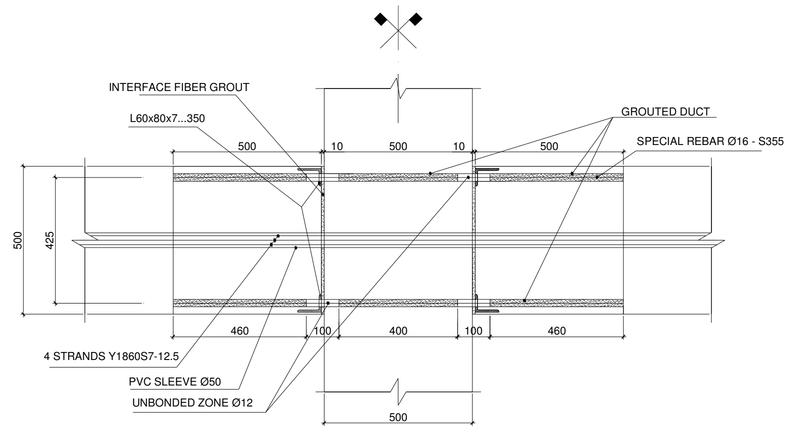

Figure 6. Detail of hybrid joint (N1 model)

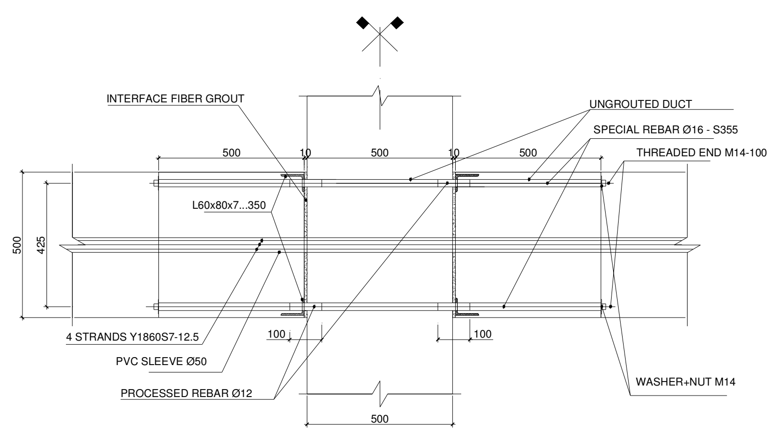

Figure 7. Detail of modified hybrid joint (N2 model)

Load history derives from the story drift one, as can be seen in Fig. 8 and respectively in Fig. 9.

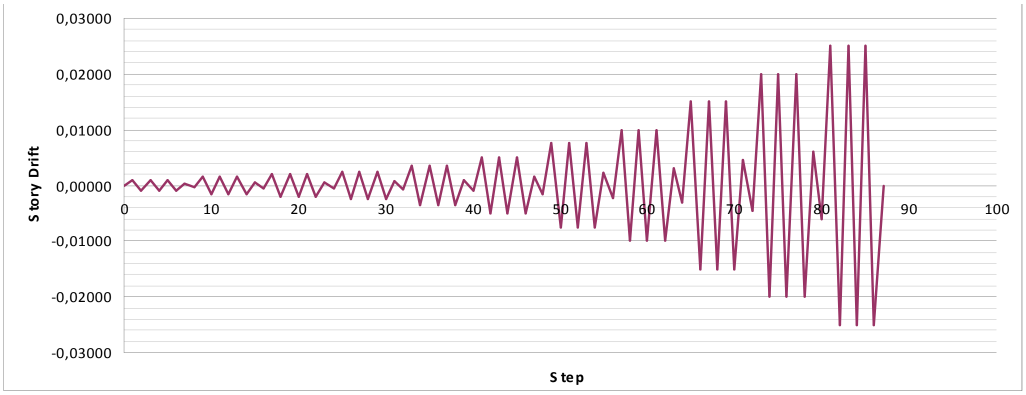

Figure 8. Story drift history

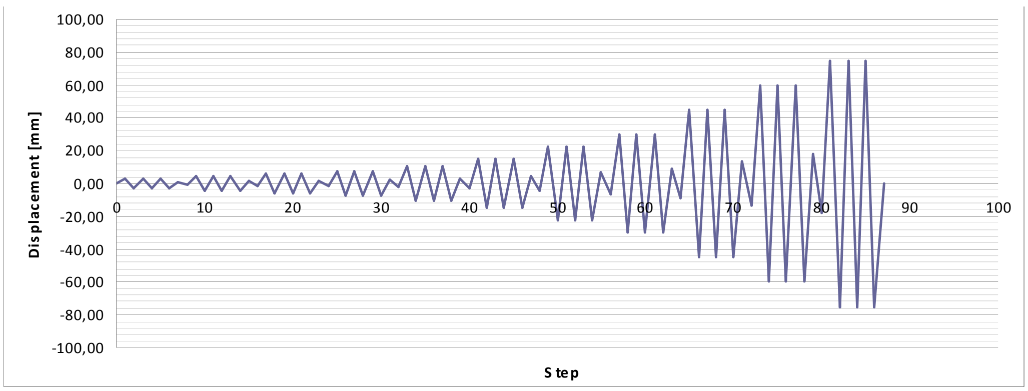

Figure 9. Load history, expressed in terms of imposed lateral displacements

The tests focused on the behavior of the specimens under lateral seismic type loadings, recording at each step, the imposed displacement corresponding lateral force, the cracking, the opening and closing of the interface crack including the behavior after the test.

The testing set up is shown in Fig. 10 and Fig. 11.

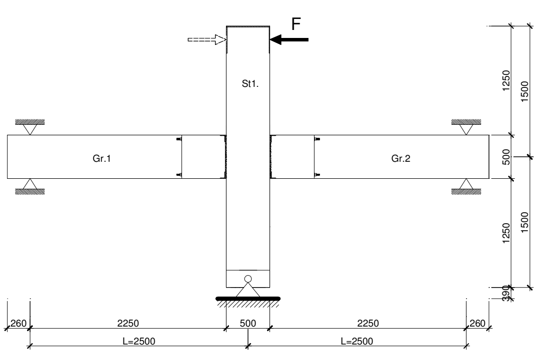

Figure 10. Testing set up sketch

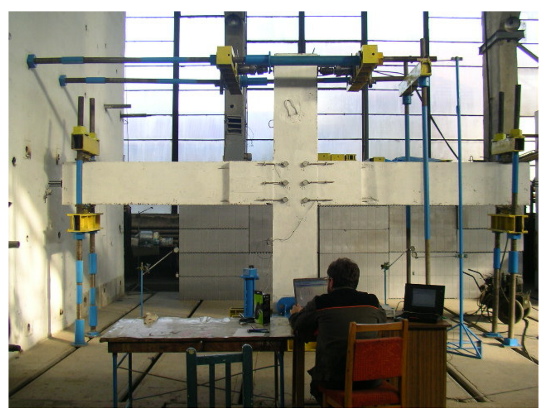

Figure 11. Actual testing set up

4. MAIN EXPERIMENTAL RESULTS

The overall behavior at cyclic lateral loading expressed by the force-displacement diagram of the hybrid joint (N1 model), is presented in Fig. 10 and respectively for the modified hybrid joint (N2 model), in Fig. 11.

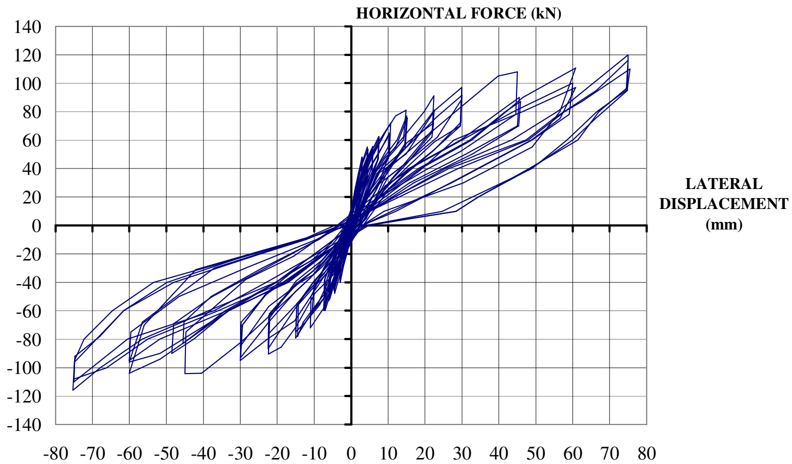

Figure 10. P-Δ diagram for hybrid joint (N1 Model)

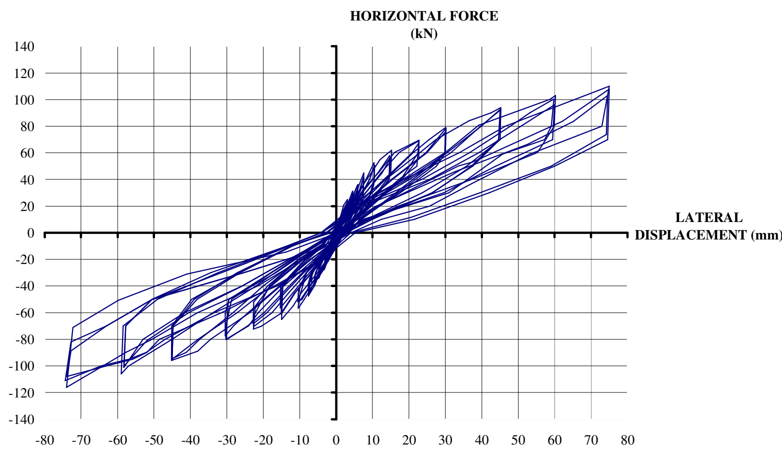

Figure 11. P-Δ diagram for modified hybrid joint (N2 Model)

The opening of the interface crack recorded at the maximum lateral displacement versus the theoretical assumed mechanism, for the hybrid joint is shown in Fig. 12 and in Fig. 13 and respectively for the modified hybrid joint in Fig. 14 and in Fig. 15. In both cases, the assumed mechanism to develop in joints of hybrid moment frames, subjected to seismic type loading is validated by the tests.

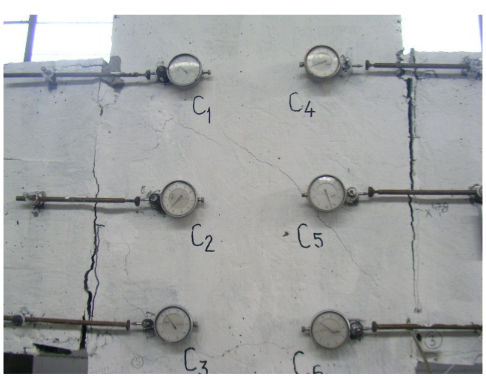

Figure 12. Interface crack opening (N1)

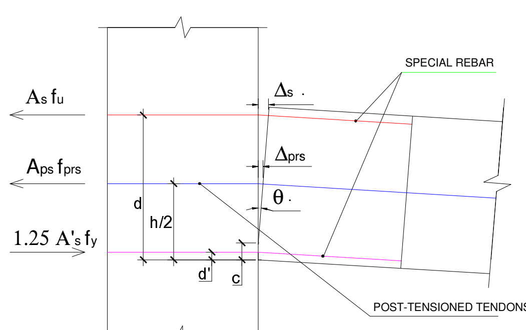

Figure 13. Joint mechanism //

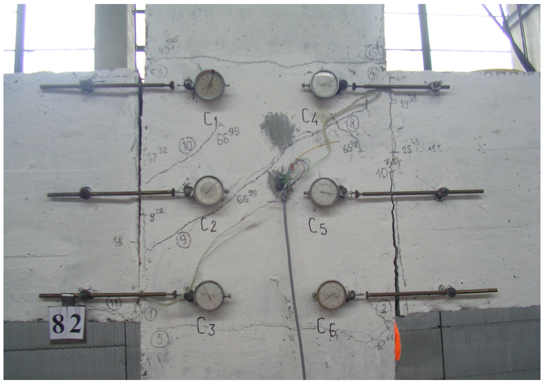

Figure 14. Interface crack opening (N2)

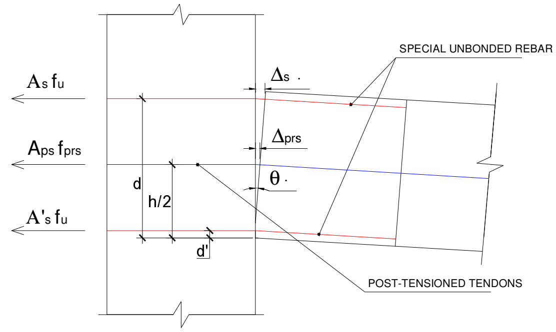

Figure 15. Proposed joint mechanism

Except of the interface crack, few other occurred during the test, all of them having maximum openings less then 0.20mm. The rigid body movement of the members was mostly revealed by the test.

5. DISCUTIONS

The probable flexural strength was estimated using the equations according to the American code (ACI T1.2-03, 2010) for N1 model.

For the N2 model, a new set of equations for the probable flexural strength of modified hybrid joint estimation are proposed, based on the mechanism shown in Fig. 15. Bernoulli's hypothesis is respected. The strands tension increase shall be considered as a sum of all interfaces elongations. The special rebar elongation (Δ_s) at the column-beam interface is estimated, due to both elastic and post elastic deformations:

$$\Delta_s = (\varepsilon_y\, l + l_d\, d_b) \qquad (1)$$

where:
ε_y - yield strain of special rebar;
l - special rebar "screw to screw" length;
l_d - development length of special rebar;
d_b - processed zone diameter.

The elongation of post-tensioned tendons, due to joint opening (Δ_{prso}), can be estimated, using the notations in Fig 15:

$$\Delta_{prso} = \Delta_s\, [(h/2-2d')/(d-2d')] \qquad (2)$$

The growth of tension in tendons ($\Delta\sigma_{prso}$) is given by the equation:

$$\Delta\sigma_{prso} = n\, \Delta_{prso}\, E_p/L \qquad (3)$$

where:
n - number of beam-column interfaces;
L - tendons length between anchorages.
E_p- elasticity modulus of prestressed tendons

The probable flexural strength at the beam-column interfaces is estimated as the sum of the contribution of special bars and prestressed tendons:

$$f_{prs} = f_{se} + \Delta\sigma_{psro} \quad (4)$$

where:
f_{se} - effective stress in post-tensioning tendons, after allowance of all prestress loses;

$$M_{pr} = [A_{ps} f_{prs} (h-\beta_{2c})/2 + A_s f_u (d-d')] \quad (5)$$

A_{ps} - upper special reinforcement area;
A'_{ps} - lower special reinforcement area;

$$\beta_{2c} = \frac{A_{ps} \cdot f_{prs} + (A_s + A_s^{'}) \cdot f_u}{0.85 \cdot f_{C'}^{'} \cdot b} \quad (6)$$

where:
f'_c - concrete strength for accidental loading;
b - column (or beam end) width.

The probable flexural strength and the test results are briefly presented, for both types of hybrid frame joints, in Table 4.

Table 4 Probable and test flexural strength

N1 Model		**N2 Model**	
Estimated flexural strength (kNm)	Test flexural strength* (kNm)	Estimated flexural strength (kNm)	Test flexural strength* (kNm)
157.6	150.6*	160.3	144.2*

* = Flexural moment corresponding to the maximum lateral displacement of 75mm.

The tests revealed a good and predictable behavior of both the hybrid joint and modified hybrid joint when subjected to seismic type loading.

The proposed design equations for the modified hybrid moment frame RC structures should be validated by further tests and detailing provisions.

6. FINAL REMARKS

The modified hybrid joints could be an attractive option for RC structures in high seismicity locations, when proper expertise is gathered, as they provide, beside the advantages of the basic hybrid frames, at least three more.

As a consequence of the fact that yielding occurs only in tension, regardless the direction of the seismic action, they are more reliable the basic hybrid joints where the special reinforcement is alternatively post elastic stressed, because no uncontrolled failure is possible due to repeated buckling combined to tension.

Removability of special unbonded reinforcement bars and thus restoring of the structural integrity after an accidental loading is another key benefic feature, involving low cost post earthquake repair.

Another benefit concerns in easy monitoring of the building after events compared with traditional structures, mainly due to the fact that the observation points are clearly located and the damages can be simply verified.

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