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# Seismic Behavior of Self-Balancing Post-Tensioned Reinforced Concrete Spatial Structure

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***Abstract*—**The construction industry is currently trying to develop sustainable reinforced concrete structures. In trying to aid in the effort, the research presented in this paper aims to prove the efficiency of modified special hybrid moment frames composed of discretely jointed precast and post-tensioned concrete members. This aim is due to the fact that current design standards do not cover the spatial design of moment frame structures assembled by post-tensioning with special hybrid joints. This lack of standardization is coupled with the fact that previous experimental programs, available in scientific literature, deal mainly with plane structures and offer little information regarding spatial behavior. A spatial model of a modified hybrid moment frame is experimentally analyzed. The experimental results of a natural scale model test of a corner column-beams sub-structure, cut from an actual multilevel building tested to seismic type loading are presented in order to highlight the behavior of this type of structure. The test is performed under alternative cycles of imposed lateral displacements, up to a storey drift ratio of 0.035. Seismic response of the spatial model is discussed considering the acceptance criteria for reinforced concrete frame structures designed based on experimental tests, as well as some of its major sustainability features. The results obtained show an overall excellent behavior of the system. The joint detailing allows for quick and cheap repairs after an accidental event and a self-balancing behavior of the system that ensures it can be used almost immediately after an accidental event it.

***Keywords*—**Modified hybrid joint, seismic type loading response, self-balancing structure, acceptance criteria.

## I. Introduction

THE concept of self-balancing structures is focused on a new design approach which also makes use of advanced materials. This new concept is based on experimental studies on the behavior under seismic type loads of a different kind of reinforced concrete frame structure. This precast reinforced concrete frame is assembled by non-adherent partial post-tensioning. Furthermore, a new detailing of column girder joints is used, as only pre-stressing reinforcement and special reinforcement cross the column beam interface. Between the precast members a fiber reinforced grout is cast.

A detailed exposure of the assembling system and column-beam connections for this type of moment frames are given in [1] and for modified hybrid joints in [2], [3].

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The case study analyzes the behavior of a corner spatial sub-structure, which includes a column and two adjacent perpendicular girders, under seismic type loads. A particular feature of the test is that the seismic type lateral loading is acting about an oblique direction with respect to the main axes of the structure, respectively spatial model.

## II. Test Model

After a series of tests on plane models of special and modified hybrid moment frames composed of discretely jointed precast concrete members assembled by post-tensioning [2], [3] the 3D behavior of this structure under lateral seismic type loading is to be studied. The full scale 3D model represents a corner of a multilevel building, expanded around the intersection to mid span of the adjacent columns and in the horizontal plane including the beams and the other adjacent columns-beam intersections, as can be seen in Fig. 1.

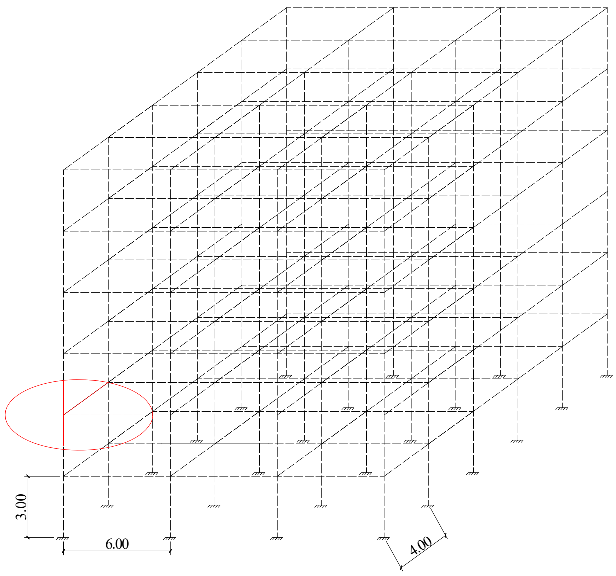


Fig. 1 Actual analyzed structure

The location of the actual building has a design ground motion acceleration of 0.24g. The seismic forces are determined using the direct displacement-based seismic design method [4]. The full scale model was assembled of precast reinforced concrete members as shown in Fig. 2. The dimensions of the model members are: beams 200x450x5500 mm, the corner column 500x500x3000 mm and the other two columns ends 500x500x500 mm.

Fig. 2 Precast RC members

The designed concrete class is C30/37 and the reinforcement bars are type PC 52 ($f_y$=345MPa). The actual compressive resistance of the concrete, obtained on samples cured in the same conditions as the specimens, on the test day, is $f_c$ = 41 MPa, and the actual mechanical characteristics of the reinforcement steel are given in Table I.

TABLE I
PASSIVE REINFORCEMENT CHARACTERISTICS

| $R_{eH}$ [MPa] | $R_m$ [MPa] | $A_t$ [%] |
|---|---|---|
| 450 | 526 | 12.5 |

Before post-tensioning the model, the adjacent surfaces between column and beams, 15 mm wide, were filled up with fiber reinforced cementitious grout, as illustrated in Fig. 3. The mechanical characteristics of the grout, determined on the samples cured in the same conditions as the model, determined on the test day, are presented in Table II.

Fig. 3 Column-beam interface detail

TABLE II
GROUT CHARACTERISTICS

| $f_c$ [MPa] | $f_{ct}$ [MPa] |
|---|---|
| 66 | 5.3 |

The model was assembled by post-tensioned strands placed in the centroid of the beams, another specific characteristic of this moment resistant frame, as seen in Fig. 4.

The pre-stressed reinforcement consists of four strands on each direction, of EN 10138-3-Y-1860-S7-12.9-R1-F1-C1 steel.

Fig. 4 Pre-stressing of the strands

The pre-stressing force is determined out of two conditions: the first is to assure the shear force transfer from the beams to the column by friction emerged due to the compressive force at the horizontal connections and the second to have enough available strain to remain in elastic range even at the top lateral loading. The prestressing force is 300 kN in each direction, less than the nominal capacity of the strands. This is another main feature of these moment frames, namely the use of partially pre-stressing.

Another particular characteristic of these frames assembled by post-tensioning is that the strands are non-adherent with respect to the structural elements.

The special reinforcement, connecting the ends of the beams through the column, made out of M14 threaded rods, group 4.8, with the actual mechanical characteristics presented in Table III, is fixed at each end with nuts and washers as seen in Fig. 5.

TABLE III
SPECIAL REINFORCEMENT CHARACTERISTICS

| $R_{eH}$ [MPa] | $R_m$ [MPa] | $A_t$ [%] |
|---|---|---|
| 422 | 476 | 11.5 |

Fig. 5 Special reinforcement and prestressing strands column fixing details

## III. TEST PROGRAM

The experimental programme is performed on a static scheme as presented in the sketch in Fig. 6. The practical realization of the testing set-up, including supporting and loading systems, is shown in Fig. 7. As can be seen in Figs. 6 and 7, although the model is symmetrical in the horizontal plane, the supporting system determines the spatial model

(N3) to represent a corner joint of the actual structure extended to the mid spans of adjacent members.

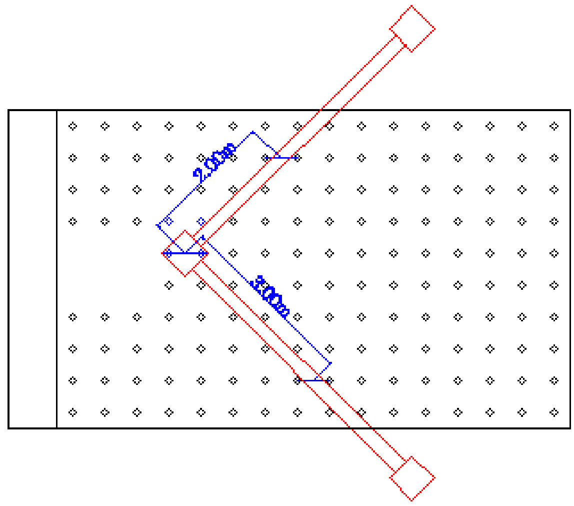

Fig. 6 Supporting sketch of the spatial model, top view

Fig. 7 Actual testing set-up

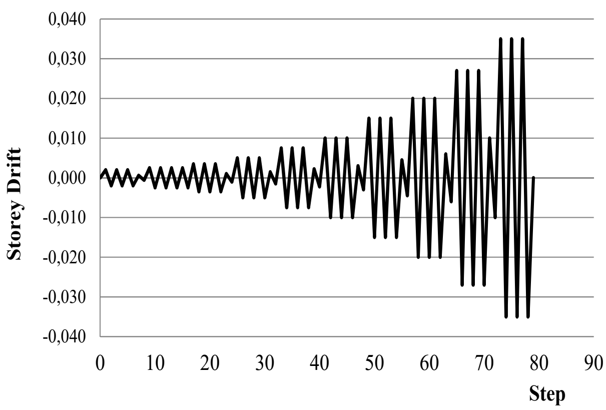


Fig. 8 Loading history

An important feature of the test is the oblique direction in which the lateral forces, simulating the earthquake action, act which makes an angle of 45 degrees to the horizontal principal axes of the model. This mode of loading was selected considering both the provision of the Romanian seismic code [5] and the easiest way to study the spatial behavior of the model using a plane action of the loading system.

The loading is actually performed by the procedure of imposed displacement versus resultant force. The imposed displacements diagram derived from the storey drift ratio is shown in Fig. 8.

The test is focused on the spatial behavior of the specimen N3 under lateral, oblique acting, seismic type loading, recording at each step of the imposed displacement the corresponding lateral force, the possible appearance of cracks, the opening and closing of the column-beam interface gaps, the elongations of the pre-stressing strands and special reinforcement and the post-loading model condition.

## IV. Experimental Results

Synthetically, the best way to express the overall behavior at cyclic lateral loading is to use the force-displacement diagrams (hysteretic loops). The hysteretic loops for the top three storey drift ratios, respectively, of 0.022 (top displacement 66 mm), 0.027 (81 mm) and 0.035 (105 mm) are drawn in Fig. 9. The loops are strangled around the origin of the axes due to the fact that the non-adherent special reinforcement accumulate permanent strain after its yielding resistance is exceeded and continues to participate to bending moment transfer only after the remnant strain is exceed by the gap width.

Opposite to the behavior of the classical reinforced concrete frames under lateral loading where the deformations develop along the whole length of the members, the beams of the moment frame assembled by post-tensioning with hybrid and modified joints have preponderantly rigid body displacements and the deformations are concentrated at the column beams interface. The majority of the deformations of the beams occur due to the opening and closing of gaps (cracking) located at the column-girders interfaces, as can clearly be seen in Fig. 10. So, the most stressed and damaged zones at these frames are located only in the column-beam joints. This feature is important when considering the extent of the damages after a major accidental loading and the need of repairs and their costs.

The modified hybrid spatial joint model N3 proves a self-balancing behavior as after the removal of the external loading the remanent top displacement is 8.2 mm (only 7.8% with respect to maximum value) as can be seen also comparing the displacement illustrated in Fig. 11 versus the one in Fig. 12.

The property of self-balancing after the loading removal of the load is assured by the non-adherent pre-stressed tendons which remain in elastic range up to the highest storey drift ratio, and the most of the strain energy embedded at loading is released by elastic work at unloading.

The dissipated energy is expressed by the mechanical work done by the displacements of the spatial model during the loading and unloading cycles.

The dissipated energy for the same displacement levels as for the hysteretic loops shown in Fig. 9 is presented in Fig. 13.

It can be observed in Fig. 13 that the dissipated energy has the highest value at the first loop at each level of the imposed displacement and it decreases at the subsequent ones. The most accepted explanation of this fact is post-elastic behavior of the non-adherent special reinforcement.

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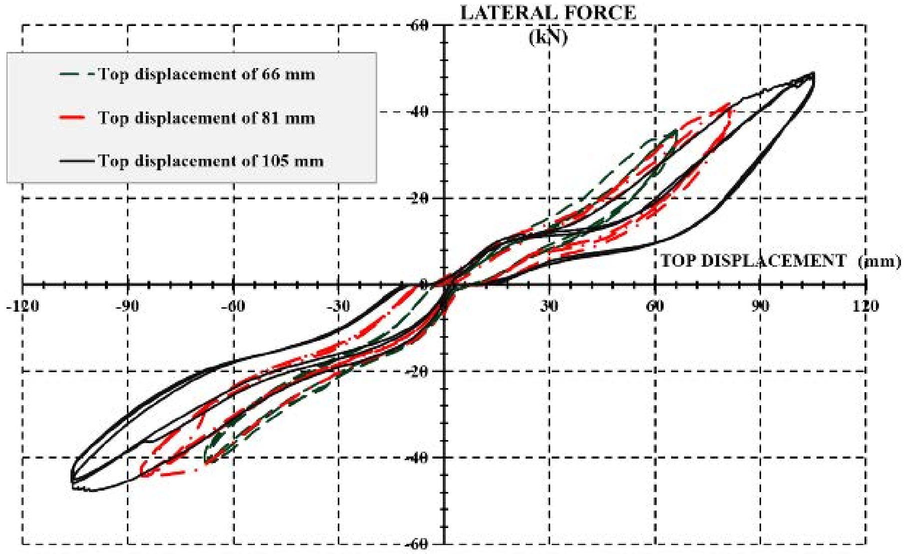


Fig. 9 Lateral load - Top displacement


Fig. 10 Rotation of the beam in modified hybrid joint at a drift ratio of 0.027, respectively a top displacement of 81mm

Fig. 11 Deformed configuration under loading

Fig. 12 Self-balancing property of spatial model

## V. Performance of the Spatial Model

Based on the actual behavior of the tested model as illustrated in Fig. 10, the design equations for the modified hybrid joint derive from the forces acting in the column-beams interfaces. Similar equations to those for internal modified hybrid joints [6], [7] are used to determine the probable bending moment for the spatial model.

The behavior of the spatial model N3 under cyclic seismic type loading history is evaluated according to the acceptance criteria [8].

The fulfillment of the given criteria by the tested model is synthetically presented in Table IV.

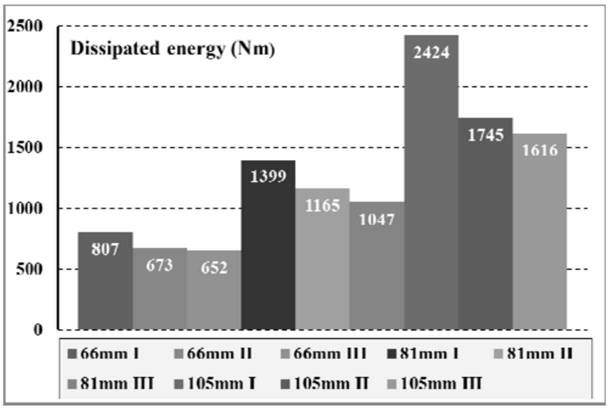


Fig. 13 Dissipated energy during the seismic type test

TABLE IV
PERFORMANCE OF SPATIAL MODEL

| Criterion | Units | Values | Realization |
|---|---|---|---|
| $E_{max}>E_n$ | kNm | $M_{max}$ (103.9) $M_n$ (93.6) | yes |
| $E_{max}<\lambda E_n$ | kNm | $M_{max}$ (103.9) $\lambda M_n$ (121.7) | yes |
| $F_{max3}>0.75 F_{max1}$ | kN | $F_{max3}$ (48.0; 47.5) $F_{max1}$ (48.0; 44.0) | yes yes |
| $\beta > 0.125$ | Nm | DE (1616) IDE (13430) | no |
| $K_{s1(\theta=0.035)}>$ | kN | $K_{s1}$(0.457; 0.447) | yes |
| $0.05K_{s2(\theta=0.002)}$ | /mm | $K_{s2}$(1.45; 1.51) | yes |

The notation in Table IV is according to [8]:

- $E_{max}$; $M_{max}$ - maximum lateral resistance of test module, determined from test results;
- $E_n$; $M_n$ - nominal lateral resistance of the test module, determined using specified geometric properties of the test members, specified yield strength of reinforcement, specified compressive strength of concrete; strength reduction factor $\phi$ of 1.0;
- $E_{pr}$; $M_{pr}$ - probable lateral resistance of test module determined using actual geometric and material properties of test members; strength reduction factor $\phi$ of 1.0; $\theta$ - drift ratio; $F_{max}$ – maxim lateral loading; $n$ – number of loading cycle at the same displacement; $\beta$ - relative energy dissipation ratio;
- $K_s$ – dissipated energy; and, $\lambda$ - column over-strength factor is 1.3, according to [5].

## VI. CONCLUSION

The behavior of the post-tensioned reinforced concrete spatial model fulfilled all the acceptance criteria, except for the relative energy dissipation ratio.

Despite that, the overall behavior is good and the self-balancing property is proved, as remnant deformation, after the loading removal, is only 7.8% with respect to maximum value of the imposed deformation that the tested structure was subjected to.

It is considered that the spatial model was subjected to higher loadings than an actual corner joint due to the fact that the contribution of the pre-stressed tendons to the lateral resistance is reduced as compared to that in the actual structure, as the total elongation of the strands represent the sum of the elongations of all "$n$" column-beam interfaces and not only the tested one, as in the test case.

Damages of model incurred during testing are concentrated at the column-beams interfaces, thus facilitating simple, quick and cost effective structural repairs to the structure [3], [6], [7].

Taking into account that the provision regarding the dissipation energy capacity at the last steps, at a story drift of 0.035 was originally referred to special hybrid moment frames composed of discretely jointed precast and post-tensioned concrete members, where the replacement of the special reinforcement is not possible, we consider that no complying this issue should not be a rejecting reason for the innovative structural design, because the repair procedure is able to re-establish almost the initial resistance and also the energy dissipation capacity.

As a final remark, the modified special hybrid moment frames composed of discretely jointed precast and post-tensioned concrete members due to its good behavior at seismic type loadings as well as its self-balancing property and retrofitting capacity may be taken into account as a reliable option for innovative and sustainable reinforced concrete structures.

## ACKNOWLEDGMENT

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## REFERENCES

[1] ACI Innovation Task Group 1 and Collaborators, "Special Hybrid Moment Frames Composed of Discretely Jointed Precast and Post-Tensioned Concrete Members (ACI T.1.2-03) and Commentary (ACI T.1.2R-03)", American Concrete Institute, USA, 2004
[2] Pastrav M. I., Enyedi C., "Hybrid Moment Frame Joints Subjected to Seismic Type Loading", in 15th World Conference on Earthquake Engineering, Lisbon, paper 1343, 2012
[3] Pastrav M., "Sustainable Structures. Seismic Type Loading Behavior of Repaired Reinforced Concrete Hybrid Joint", 13th SGEM GeoConference on Nano, Bio and Green – Technologies for a Sustainable Future, Albena, Bulgaria, 2013, pp. 465-472
[4] Priestley M. J. N., Calvi G. M., Kowalsky M. J., "Displacement Based Seismic Design of Structures", IUSS Press, Pavia, Italy, 2007
[5] Romanian Development, Public Works and Dwelling Minister, "Seismic Design Code - Part I: Building Design Provision, P100-1", (in Romanian), Bucharest, Romania, 2013
[6] Pastrav M., Baera C., Florea D., "Efficient Moment Frame Structure", in 12th International Conference on Concrete, Structural and Geotechnical Engineering, Istanbul, Turkey, 2014, pp. 1414-1419
[7] Pastrav M., Constantinescu H., Mircea C., "Performant structure design based on experimental tests", 15th SGEM GeoConference on Nano, Bio and Green – Technologies for a Sustainable Future, Vol. II, Albena, Bulgaria, 2015, pp. 211-218
[8] ACI Innovation Task Group 1 and Collaborators, "Acceptance Criteria for Moment Frames Based on Structural Testing (ACI T1.1-01) and Commentary (ACI T1.1R-01)", American Concrete Institute, USA, 2004