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REAL TIME TESTING OF REINFORCED INFILLS

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SUMMARY

The paper deals with the problem of dynamic response of R/C frames with infills subjected to accidental loading, impact effects and space seismic inputs of different composition and intensity. The large scale model was tested on Master shaking table of ISMES Italy using 6 DOF input based on Nocera record of Central Italy Umbria 1997 earthquake. Used model was 1:1 two storied reinforced concrete frame with reinforced brick masonry infills, symmetrical in *y* direction. The tests comprised ambient vibration test, impact test, sweep sine test and earthquake like *x, y, z*, θx, θy and θz common excitation with increasing intensity of seismic input. The aim of the research was to investigate in plane and out of plane behaviour of the frame with infills and its failure development. The efficiency of used reinforcing procedure is discussed and compared with traditional technologies. The applied technique provided the system with higher seismic resistance with uniformly distributed seismic capacity through the structure since the beginning of the model failure. Obtained data help to understand changes in seismic resistance of such types of structures with the regard to different elements and materials participating in the dynamic response. The obtained results bring basic view on the contribution of individual structural and non-structural parts to the total seismic resistance and the life time of similar types of structures.

INTRODUCTION

Standard and site specific response spectra are usually adopted to calculate seismic response of chosen structures and models. But mechanical application of this scheme into each situation can bring remarkable deviation from actually seismic resistant design. Therefore, in the paper few modeled situations of seismic response are analysed to point out the influence of different inputs and modeling. The other question is to understand what is the contribution to the seismic resistance when reinforced concrete frame structure with brick masonry infills is used like the resisting system. Theoretical analysis and well worked out experimental studies bring the ideas for verifications of seismic resistance capacity of new systems in which traditional and new retrofitting technique could be applied.

2. SPACE 6 DOF SEISMIC INPUT USED FOR MODEL EXCITATION

In general, actual seismic ground motion is interconnected with wave fields that consist from components of different frequencies and wave lengths. However, for practical purposes the simplifications are adopted for inputs described by response spectra or ground motion time histories. Seismic response is controlled by interaction between dynamic properties of a structure and the time and space composition of a ground motion. The structure resistance and the failure points can be concentrated into narrow regions or spread uniformly throughout the structure.

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Our approach concerns mostly the purposing response analysis with or without account for rotation seismic inputs. Either in previous researches we can find the notes on this topics, larger attention to this subject is the consequence of new codes and standards, namely Eurocode 8, Parts 2 and 3. The free field excitation in Eurocode 8 is specified by the definition of the translation motion at a point and further on by the definition of the rotation motion. The later specifies the spatial variability of the translation motion at a point. Spatial variability of seismic motion is related for structures as follows: Some structures might be sensitive to spatial varying vertical excitation; a vertical ground motion propagating in any horizontal direction is expected to promote a rocking of the structure, concurrent with the rocking provided by the horizontal excitation along that direction. The contribution of horizontal ground motions to torsion seismic input either increases the torsion response of asymmetrical structures or creates torsion response in case of symmetrical structures. Rotation response spectrum is defined in an analogous way as translation response spectrum, e.g. by consideration at a single rotational degree of freedom oscillator of natural period $T(j)$ and defined damping ζ. The reference system is acted upon by the rotation motion. Let R_θ be the ratio between the maximum moment of the oscillator spring and the rotational moment of inertia about its axis of rotation. Thus the ground motion during the earthquake is represented by three translation and three rotation either time histories or response spectra.

Rotation response spectra are in ENV 1998-3 defined by:

$$R_{\theta x}T(j)) = 1.7\ \pi\ R_x(T(j))/(V_S T(j)) \tag{1}$$

$$R_{\theta y}(j)) = 1.7\ \pi\ R_x(T(j))/(V_S T(j)) \tag{2}$$

$$R_{\theta z}T(j)) = 2.0\ \pi\ R_x(T(j))/(V_S T(j)) \tag{3}$$

where rotation response spectra are $R_{\theta x}T(j))$ = around axis x (roll); $R_{\theta y}T(j))$ = around axis y (pitch); and $R_{\theta z}T(j))$ = around axis z (yaw) in radians $.s^{-2}$;

$R_x(T(j))$ = site dependent response spectrum for horizontal excitation, in $m.s^{-2}$;

V_S = S-wave velocity, in $m.s^{-1}$;

$T(j)$ = the natural period being considered, in s.

On similar basis we can create rotation input time histories. The rotation input acting at the ground level arrives with phase shift in relation to respective translate input. The procedure includes creation of rotation input time histories and calculation of respective response spectra. Both time histories and response spectra are influenced by this phase shift and frequency effects as well.

It should be considered that when using seismic response spectra inputs, the results include independent rotation seismic response maxima attributed to respective natural modes and do not include neither arrival time of wave components nor lengths of waves related to dimensions of structure in plane. Therefore, it seems to be more convenient to apply time and space discrete modelling both for the structure and the excitation.

Large earthquake September 1997 in Central Italy in Umbria region caused the failure of many buildings constructed from reinforced concrete frames with infills. After the discussion and agreement with ISMES Seriate and University of Bucharest one from the records of this earthquake was chosen to be analysed and adopted like the control signal for tests of reinforced concrete frame with infills on Master shaking table in ISMES. The chosen Nocera record contains high amplitudes of accelerations (nearly 0.5 g in each direction). It was recorded at a distance only 11 km from the epicentre. Its general features show that the large amount of energy comes during the first 5-6 sec. Either original record lasts 45 sec, for the test purposes it was reduced to the length of 25 sec. The time histories of input accelerations including calculated rotations and respective acceleration response spectra for 2 and 5 % damping are in Figure 1.

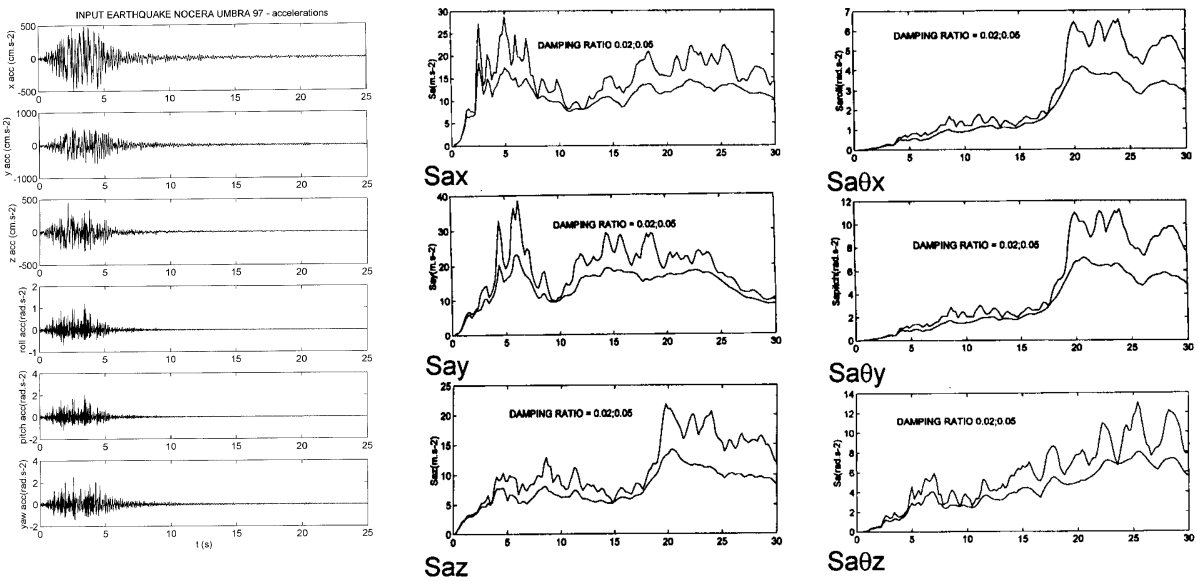

Figure 1: Acceleration time histories and response spectra of used 6DOF seismic input (Nocera 1997)

3. TESTED R/C FRAME MODEL WITH REINFORCED BRICK MASONRY INFILLS

Reinforced concrete frames with infills belong to very frequent structural systems constructed both in seismic and aseismic regions. Keeping in mind the dynamic effects contribution to the life time of a structure, the accidental seismic actions should be covered by seismic resistance based both on reinforced concrete and masonry infills parts. Naturally, the stiffness, damping and strength properties of infills are varying case to case. In spite of that, neglecting of their participation leads to the different model of seismic response than is actual one. The only way, how to overcome this problem and come to some solutions, is application of combined experimental and analytical research ([Juhásová, 1991], [Benedetti et al., 1994], [Juhásová et al., 1998], [Da Rin et al., 1996]).

Our 1:1 two storied reinforced concrete frame model with reinforced brick masonry infills was tested on large shaking table of ISMES Italy using 6 DOF input based on Nocera record of Umbria Italy 1997 earthquake prepared in ICA SAS Slovakia. The idea of plastic grids reinforced masonry was elaborated by TU Bucharest Romania and applied on the tested model ([Popa and Sofronie, 1996], [Sofronie, 1997], [Sofronie and Popa, 1998]).

The model was constructed as symmetrical in *y* direction and asymmetrical in *x* direction. Its dimensions in plan were 3.5×3.5 m, height was 5.9 m. R/C columns were of square cross section 0.25×0.25 m, girders 0.25×0.30 m, floor slabs were 10 cm thick. Two opposite masonry walls were constructed from full bricks of thickness 24 cm in the first storey and 11 cm in the second storey. Front wall had door in the first storey and a window in a second storey, back wall was full. Lime-cement mortar was used in masonry together with plastic grid reinforcement in horizontal bed joints, applied in each fifth row. 64 channel data acquisition system was used to follow accelerations, strains and displacements in appropriately chosen points. Figure 2 gives a basic information about tested model and the position of instrumentation used.

The tests comprised ambient vibration test, impact test, sweep sine test and earthquake like x, y, z, θx, θy and θz common excitation with increasing intensity of seismic input ([Severn et al. 1998], [Juhásová, 1999]). However, the short duration of strong earthquake phase did not allow to develop low cycle fatigue like behaviour with development of hysteresis loops in critical sections of system. The strength in critical points was decisive and redistribution of stresses during the response was affected both by input and natural modes of vibration.

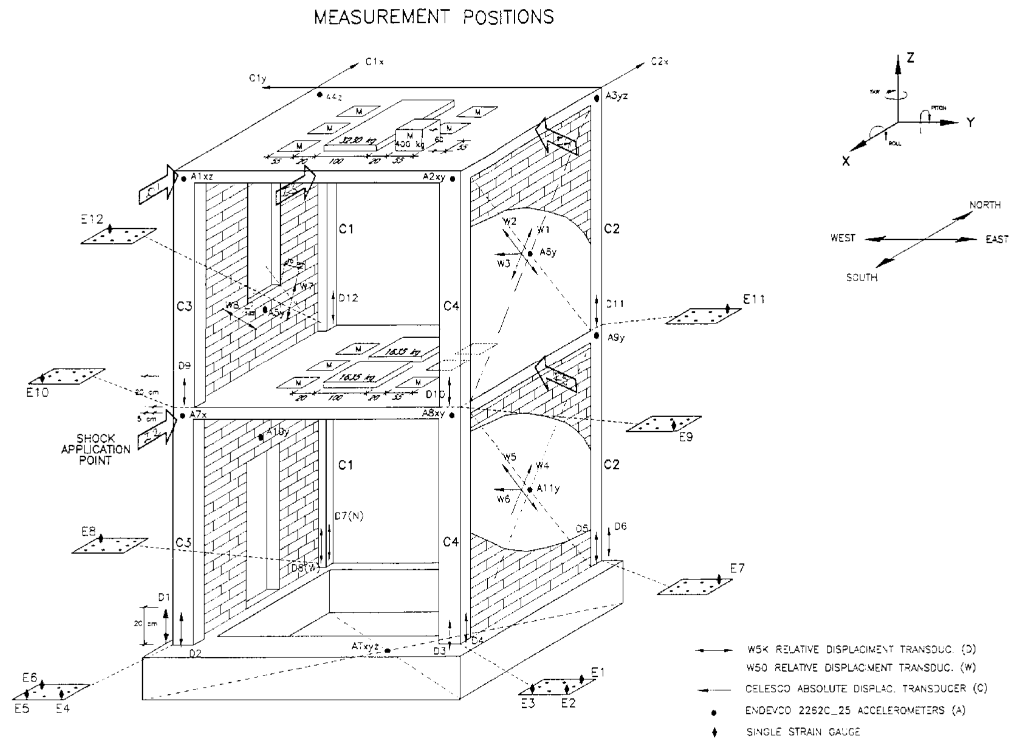

Figure 2: Tested R/C frame model with infills and its instrumentation

In analytical model we can apply simplified or more sophisticated approach. But keeping in mind practical purposes, the linear FEM model was calibrated using material properties based on laboratory investigations and previous experiences. Calculated lower natural modes are in Figure 3.

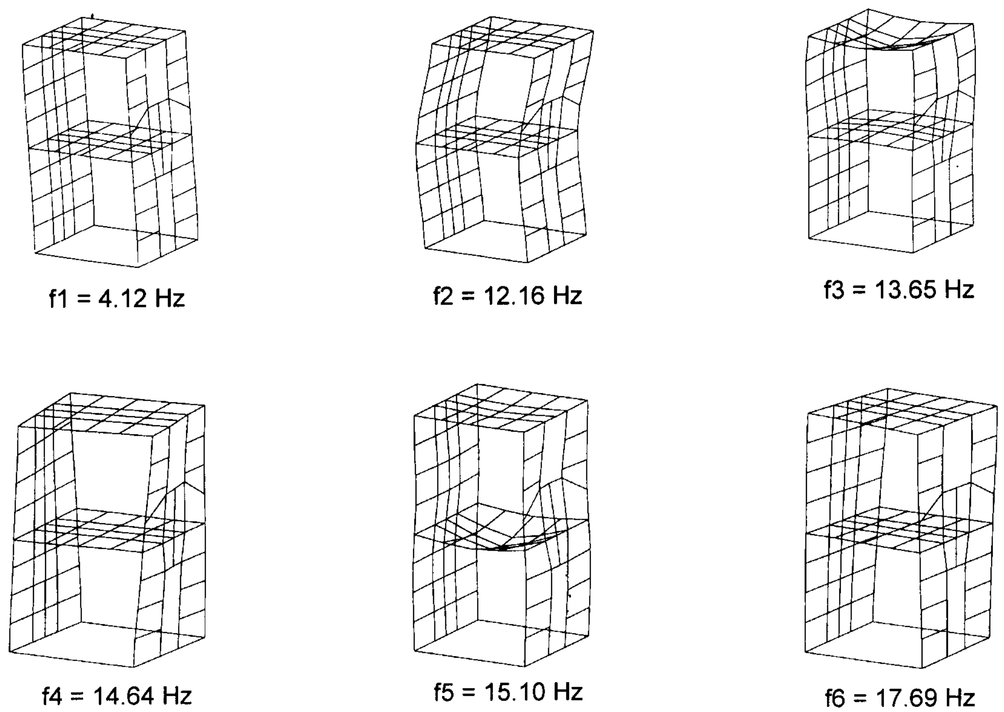

Figure 3: Calculated natural modes (used Young moduli: 30 GPa - concrete; 2 GPa - brick masonry)

From experimental results it is worth to pick up following observations:
The experimental dynamic identification of the model was successfully completed both for the cases of stiff and partially ductile supports. Table 1 gives data about measured natural frequencies. Sweep sine test in *z*-direction gave floor slabs natural frequencies of values 17 Hz for second storey and 19 Hz for the first storey (see

calculated values of *f*3, *f*5 in Figure 3). Structural system is symmetrical in *y*-direction, where both natural frequencies were clearly identified. In *x*-direction the asymmetry of infills exists and coupled vibration *x*-θ was identified as expected. Next contribution came from boundary conditions. The natural frequencies in *y* direction were decreasing, while in coupled *x*-θ vibration lower frequency increased and upper decreased. At low level of excitation the damping was very low. Especially in *y*-direction damping ratio reached during sweep sine test only 1.5 - 2.0 %.

Asymmetrical structure with symmetrical reinforced concrete frame has shown considerable contribution of reinforced infill masonry to total stiffness and strength. Having general earthquake like 6 DOF seismic input, the yielding appeared firstly in the steel reinforcement of columns and it was followed by separation in upper horizontal and vertical connections between the frame and infill masonry. The result of this process aimed into separate cantilever like vibration of left masonry panel in the second storey of model. It should be expected that during the longer stage of extreme seismic input the out of plane failure of masonry would appear as the first one. Next stages of tests continued with partial protection of this critical part. Figure 4 presents the appearance of cracks after 0 dB test and 2 dB test.

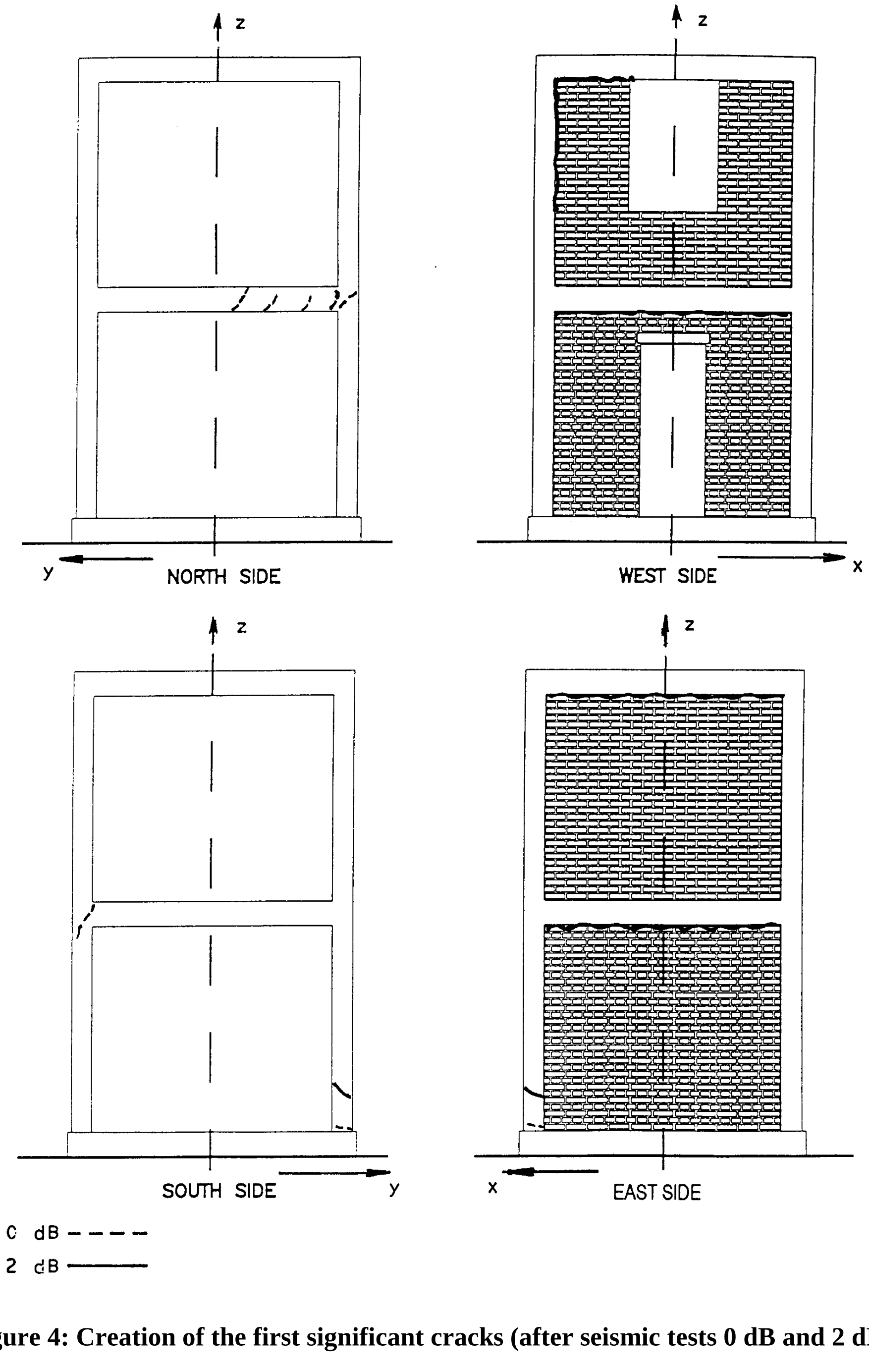

Figure 4: Creation of the first significant cracks (after seismic tests 0 dB and 2 dB)

Table 1: Measured natural frequencies of tested model. (The row for ambient test gives in brackets the calculated values for the model with added floor masses. Added floor masses represent the imposed loads on both floor slabs)

Natural frequencies (Hz)	$(x\text{-}\theta)_1$	$(x\text{-}\theta)_2$	$(\theta-x)_1$	$(\theta-x)_2$	y_1	y_2
Ambient(1) without masses - stiff	9 (7.69)	54 ? (46.15)			4 (3.42)	12 (10.26)
Impact(1) with masses - stiff	8.3	27	13.1	37	3.5	10.3
Impact(2) with masses - duct.	12.0	27.5				
Sweep sine x with masses - duct.	11.4	24.4	12.8	37?	2.9	9
Sweep sine y with masses - duct.					2.75	9

The obtained results have shown that the failure appeared due to combined effect of lateral and torsion vibration and that the vulnerable crucial points were in upper horizontal and in vertical connections between frame and infill walls, mainly those in the left upper corner of upper storey infill wall with window. After partial separation of the masonry panels from the frame both in horizontal and vertical connections, the separate parts of infills behaved as a single cantilever wall with remarkable vibration out of the plane. The identification tests of the model using ambient excitation, impact tests and sweep sine tests gave enough data to determine natural frequencies of tested model before any failure appeared.

6DOF seismic excitation induced prevailing dynamic deformations in y direction where R/C frame contribution to the seismic response was dominant. Cracks started in R/C frame joints with simultaneous yielding of steel reinforcement in critical sections. Development of steel strains E7, E8 can be seen in Figure 5. Increase of strains in time during 2 dB test run is in the left chart. Partially reconstructed cumulative strains are in the right chart. Extreme values correspond to maximum, minimum and residual values of strains after each available seismic test run. It is worth to emphasise that after 4 dB seismic test run with 6DOF, the input was changed to 2 DOF one using only x and θy - pitch components. Thus, the redistribution of stresses produced decreasing of strains in R/C frame and the increase of those in reinforced masonry. Out of plane vibrations of walls were reduced and the local failure in wall panels was spread through all panel area with prevailing separations of bricks at the corners and in the vicinity of wall openings.

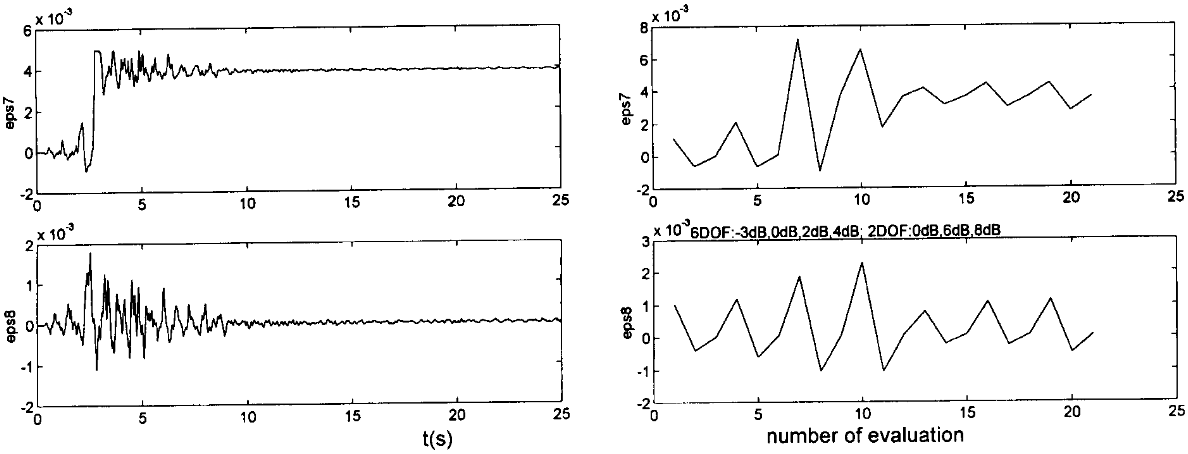

Figure 5: Time histories of strains in steel rebars E7, E8 (left) and their cumulative damage with the change of seismic input (right)

In view of Figure 5 and Table 2 the increase of 2 DOF seismic input up to 8 dB did not cause such stresses in the frame like 6 DOF seismic inputs with lower intensity. The in plane behaviour of masonry wall panels was excellent, the diagonal cracks did not appear due to the beneficial effect of plastic reinforcement. Thus, the most vulnerable points were critical sections of the R/C frame and the joints between frame and masonry infills. Out of plane vibration of masonry infills was accompanying phenomenon. Examples of cracks in R/C frame after the end of test are in Figure 6.

Table 2: Chosen measured extremes in seismic response of the tested model

Test N.	Input (dB)	Input (DOF)	Milistrains (steel)	Relative deflections (concrete) (mm)
20	0 dB	6 DOF	E1>2; E1res =1.48;	-
21	2 dB	6 DOF	E1>4 - broken; E7>5; E7res=3.9;	D4=2.13 mm;
22	2 dB rep.	6 DOF	E7=11.9; E7res=7.6;E2=4;E2res=0.8;	D4=2.2 mm;
25	4 dB	6 DOF	E6=6.3; E6res=1.9;	D5=2.1 mm; D8=2mm;
30	8 dB	2 DOF	-	D11=1.6 mm;

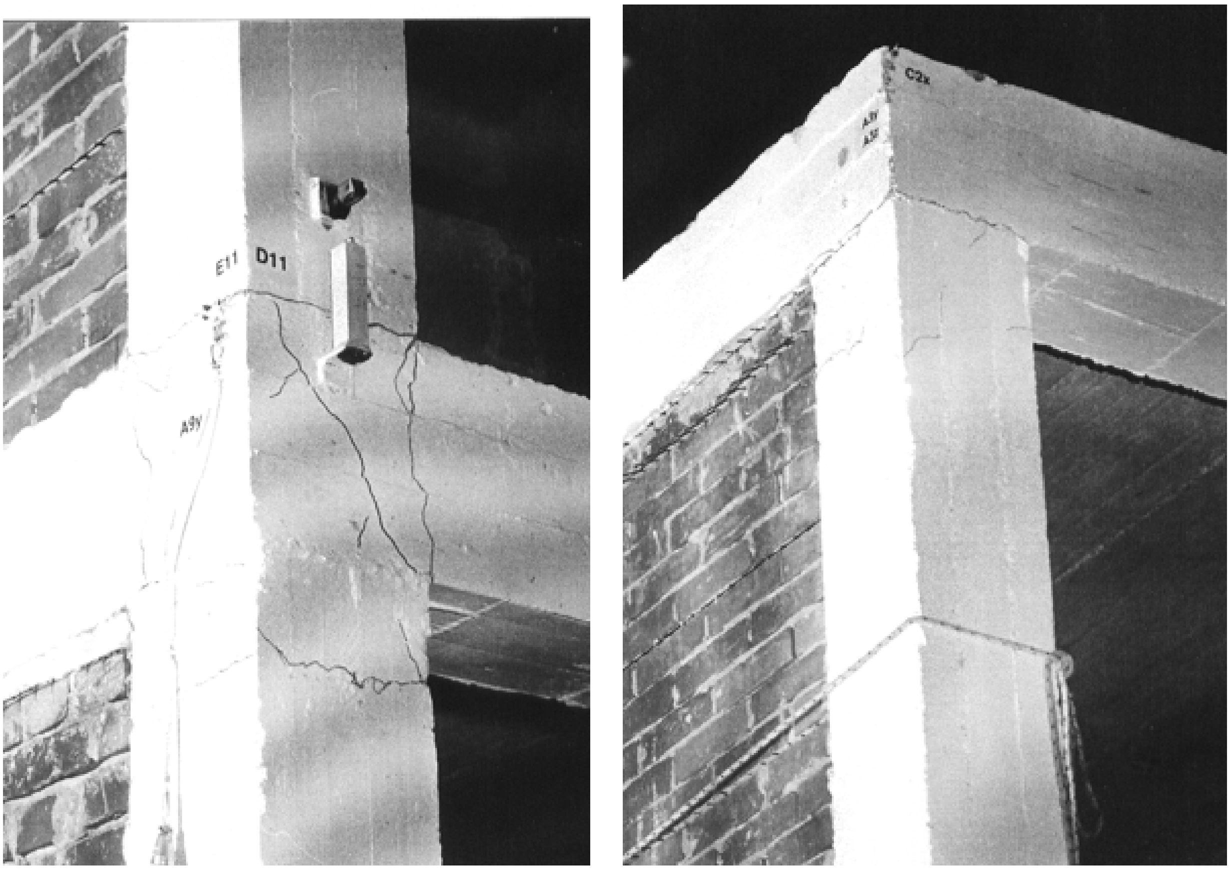

Figure 6: View of cracks in R/C frame columns after the seismic test

4. CONCLUSIONS

Tests of full scale model on large shaking table were realised using original, appropriately modeled 6 DOF seismic input based on actual strong earthquake. The numerous obtained data describe redistribution of seismic resistance between R/C frame, masonry infills, boundary joints and the plastic reinforcement in masonry.

Observations from historical and past earthquakes of this century suggest that the rotation response is larger than that considered solely on the basis of the response to pure translate inputs. The results of theoretical and experimental analysis of symmetrical and non-symmetrical models confirm such ideas Space seismic response differs from the plane one. Therefore, both structural model and inputs should be built in space mode. Such approach implies changes in natural frequencies and modes of vibration. Different positions of initiative failure regions should be expected in relation to used structural model and inputs. Rotation seismic inputs cause the increase of stresses in edge structural elements. Remarkable torsion effects can appear also in case of symmetrical structures. The increase of stresses is obvious in torsion-translate response of asymmetrical structures. The important task arise to pay larger attention to rotation seismic inputs and to spread the response analysis to combined inputs.

It should be emphasised the necessity of the continuous control of seismic resistance capacity in critical parts of the structure. Simultaneously, the appropriate changes should be introduced into structural model depending on the degree of its non-linear behaviour. The verifications of stresses in critical parts give the answer whether the design is sufficient or it should be modified. The described case study proved that it is possible to reach such combination of reinforced frame with infill masonry walls which gives nearly uniform seismic resistance capacity and remarkable contribution of infills to total seismic resistance of structure. However, appropriate joint details design and treatment at the frame and infills boundaries need further studies and optimization. Large shaking table tests gave original data for next research and design purposes. This is important both for construction of new structures and for the upgrading of existing ones, as far as these types of structures were and are frequently built all over the world.

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