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Finite Element Model Updating of a Steel–Concrete Composite Moment-Resisting Structure with Partial Strength Joints

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Abstract. Dynamic and static identification of a full scale moment-resisting steel-concrete composite structure with partial strength joints that was tested by means of the pseudo-dynamic testing technique at the ELSA laboratory of the Joint Research Centre at Ispra, Italy, is the subject of this paper. The structure was subjected to pseudo-dynamic and dynamic tests at different damage and peak ground acceleration levels; and the results were used for identifying the behaviour of the structure. Two and three-dimensional refined finite element models of the structure accompanied by a robust nonlinear optimization method, the Powell's Dog Leg method, were updated in order to reproduce in an optimal fashion the experimental static and dynamic behaviour of the structure.

Introduction

Inspection, identification and damage detection of aging and after-earthquake structures by means of non-destructive dynamic tests constitute an important aspect concerning structural health condition assessment. The important fact behind structural damage detection techniques is that the main structural characteristics such as dynamic and stiffness properties change owing to the damage. With regard to the dynamic identification of the structure at different damage levels, a 3D Finite Element (FE) model was updated with a nonlinear optimization method named the Powell's Dog Leg, by means of experimental extracted modal data, i.e. natural frequencies and modal displacements. During the cyclic test rotations of joint components, i.e. shear panels and connections, were used for identifying the behaviour of joints; and a 2D FE model of the structure was updated under cyclic loads. In order to avoid numerical problems detecting the inelastic behaviour during Model Updating (MU), when the secant stiffness approaches zero, a novel technique based on transferring data coordinates to their maximum value coordinate at each half cycle was implemented.

Characteristics of the structure and test programme

The partial-strength steel-concrete composite Moment-Resisting (MR) structure under test was made up of three identical frames in the main direction with the equal distance of 3m and reinforced with X-shaped braces in the transverse direction. A side view of the structure is shown in Figure 1. Detailed information about the test structure and its design is reported in [1]. In order to investigate different performance objectives, four Pseudo-Dynamic (PsD) tests at different pga - 0.1g for the elastic behaviour, 0.25g for the serviceability limit state, 1.4g for the ultimate limit state, 1.8g for the collapse limit state - and a final cyclic test were carried out. Three vibration tests were also performed at different damage levels: phase 1, on the undamaged structure; phase 2, after the 1.4g pga PsD test for the damage identification at the ultimate limit state; phase 3, after the final cyclic test, at the collapse limit state. The cyclic test was carried out by applying a displacement history at the top storey and fixing the ratio between the actuator reactions at the bottom over that at the top storey to 0.97; this ratio was calculated from the modal properties of the structure [1]. The displacement histories of both stories are illustrated in Figure 2.

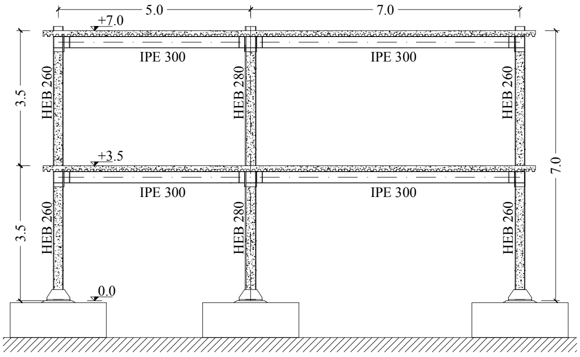

Fig. 1. Side view of the test structure. Dimensions in m.

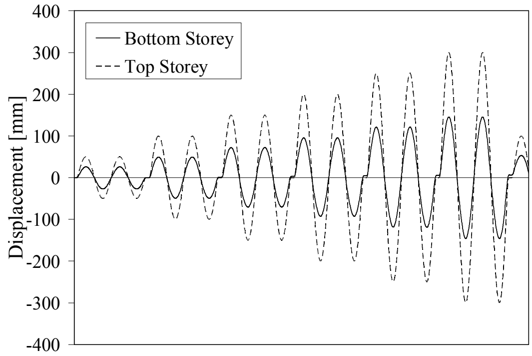

Fig. 2. Displacement history for the cyclic test.

Model updating of the structure under cyclic test

Thirty-two measurements of the cyclic tests in the form of time series, including rotations of joint components, external forces and storey displacements, were used for the MU of the test structure; to this end, a refined 2D FE model with 168 DoFs, as illustrated in Figure 3, was implemented. Web panel and connection deformability are modelled by means of rotational elastic springs. The detailed joint model is shown in Figure 4. Twenty-five parameters relevant to rotational stiffnesses of different joint components and flexural stiffnesses of beams and columns were assigned [2,3]. In order to minimize the sum of the squares of the errors between the results of the model and measurements, that are non-linear functions of the assigned parameters [4], a robust non-linear optimization method, the Powell's Dog Leg [5], was applied to the updating of the FE model of the structure. In order to identify the inelastic behaviour of the structural components, the secant stiffness approach was implemented. For avoiding numerical problems when the secant stiffness of the elements approaches zero, a novel method based on transferring the coordinates of the measured time series to their maximum value coordinates at each half cycle was implemented [2]; the procedure is depicted in Figure 5. The comparison between the identified force-displacement values and the measured ones at bottom and top storeys are presented in Figure 6 and Figure 7, respectively. A good agreement between experimental and identified results is evident. Figures 8÷10 illustrate the results of the identified moment-rotation of some of the joint components and a base joint.

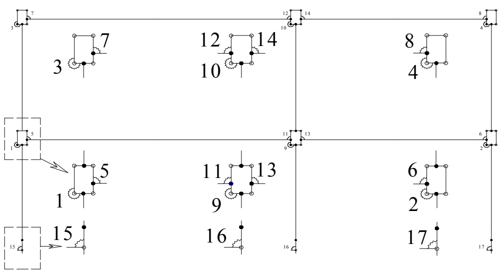

Fig. 3. The 2D FE model of the interior frame for static identification

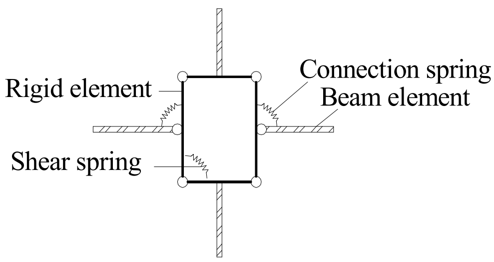

Fig. 4. 2D model of the joint for static identification.

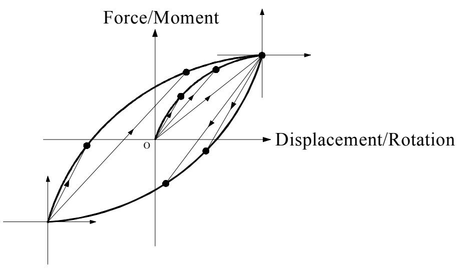

Fig. 5. Identification steps for each half cycle

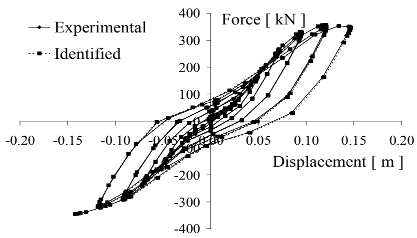

Fig. 6. Force vs. displacement of the bottom storey.

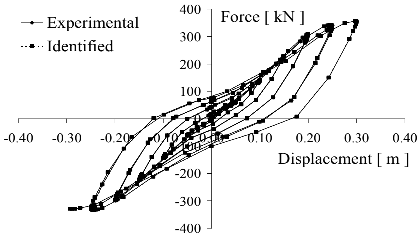

Fig. 7. Force vs. displacement of the top storey.

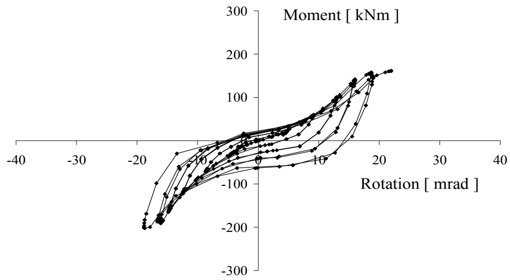

Fig. 8. Identified connection, Spring No. 8.

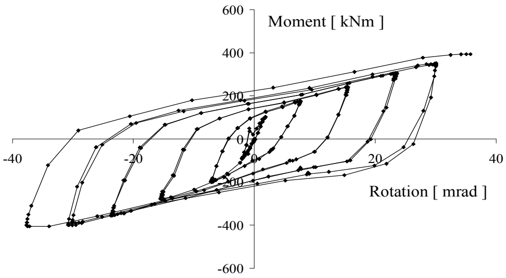

Fig. 9. Identified shear panel, Spring No. 9.

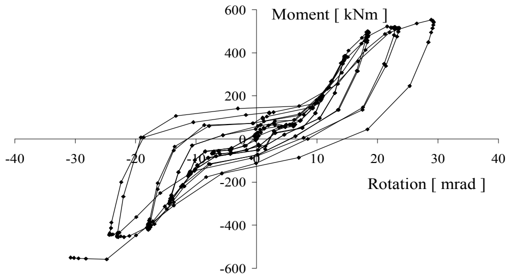

Fig. 10. Identified base joint, Spring No. 16.

Vibration Tests and Modal Extraction

Vibration tests aimed at detecting and locating the damage undergone by the structure following PsD and cyclic tests. Three different accelerometer configurations were set up in each test phase: the global A configuration aimed at describing the overall structural dynamic behaviour; the B and C local configurations were devoted to the analysis of the interior and exterior first floor beam-to-column joints, respectively.

Stepped Sine Tests (SST) and Shock Hammer Tests (SHT) were performed in the three test phases described above, exciting the structure with an electro-magnetic shaker and an instrumented sledge-hammer, respectively. The location of the harmonic exciter and the impact points are indicated in Figure 11; while the accelerometer configuration B is reproduced in Figure 12.

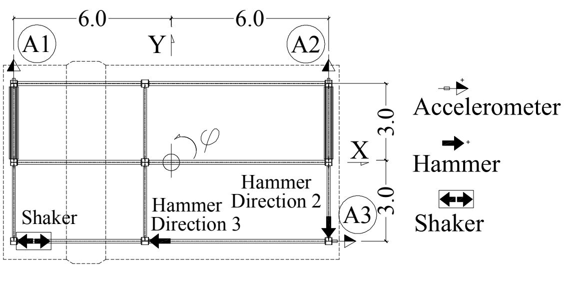

Fig. 11. Location of shaker, hammer impact points and accelerometers at the top storey. Dimensions in m.

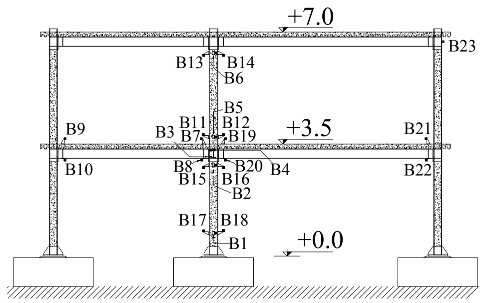

Fig. 12. Location of accelerometers in the configuration B. Dimensions in m.

The six lowest natural frequencies, corresponding to the first and second longitudinal, transversal and torsional natural modes, were successfully detected by means of the forced tests. The Frequency Response Function (FRF) plot of the accelerometer A3 is reported in Figure 13, while experimental modal data, extracted with the circle fitting technique, are presented in Table 1. The location of accelerometers around beam-to-column joints, depicted in Figure 14, derives from the mechanical model sketched in the same figure. Except for the beam position, the joint model is similar to the static one, taking into account connection and web panel deformability. Details on the test set-up and the full set of experimental data are included and commented upon in [6,7].

The progressive reduction of the natural frequencies and the increase of the proportional damping coefficients owing to damage, which represents a typical behaviour of moment resisting structures, is clearly detected.

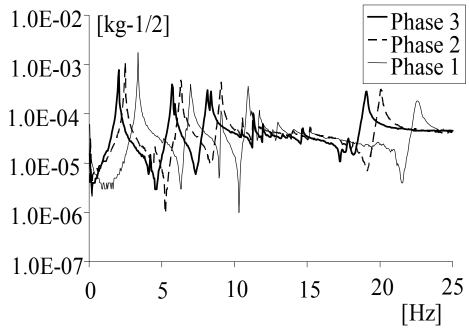

Fig. 13. Plot of the accelerance amplitude acquired with the A3 accelerometer. (See figure 11.)

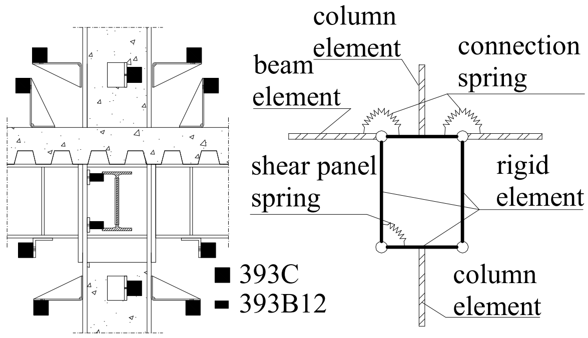

Fig. 14. Accelerometer set-up around an interior joints and its mechanical idealization

Table1. Experimental natural frequencies and damping coefficients extracted both from SHT and SST tests: averaged values.

Mode	Phase 1		Phase 2		Phase 3	
	Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]
1	3.36	0.57	2.38	1.27	1.95	1.44
2	5.09	0.66	4.44	0.83	4.15	0.96
3	6.92	0.70	6.24	0.67	5.70	0.68
4	10.94	0.69	8.95	0.61	8.18	0.90
5	16.48	0.49	13.95	0.30	13.72	0.59
6	22.52	0.76	19.97	0.54	19.05	0.44

Results of the Modal Updating

The 3D FE model sketched in Figure 15, whose interior frame is shown in Figure 16, was updated in the three dynamic test phases. The assumption of rigid diaphragm conditions, besides the joint model of Figure 14, was retained. The damage induced by the PsD tests was quantified and located by comparing the FE stiffness values identified in the different tests. The five lowest natural frequencies could be evaluated, allowing to simultaneously update three parameters, linked to the elastic stiffness of braces, columns, connections and base joints. The FE code and the MU procedure were implemented in an expressly written code, using the Fox and Kapoor formula and the Nelson method [8], in order to evaluate the eigenvalue and eigenvector sensitivity, respectively. The mass matrix, evaluated with a lumped mass model, was retained as deterministically known. The Dog-Leg method [5] was successfully applied for the minima search, leading to a faster and more reliable convergence than the damped Gauss-Newton method.

The MU permitted to match the five lowest experimental natural frequencies: in detail, the identified frequency values are collected in Table 2; while the identified FE stiffness values are reported in Table 3. Each parameter, reported in the first column, was applied to all the corresponding stiffness detailed in the second column, with additional assumptions. It was detected: i) the small degradation of the column stiffness, limited to 3.4%; ii) a continuous important reduction of X-shaped bracings stiffness and of beam-to-column connections, reaching 30%; iii) the very high decrease of the base joint rotational stiffness between Phases 1 and 2, equal to 91%, corresponding to the observed yielding of the anchoring bars. The diagonal MAC coefficients, gathered in Table 4, show the good correlation obtained between identified and experimental modal displacements.

A joint model similar to the employed one was also implemented in a 2D FE model. In this case, only two experimental reference frequencies could be used. Relevant results are reported and commented upon in [9]. The 3D model, taking into account 5 numerical frequencies, permitted a more complete exploitation of experimental data, even if an increased number of unknowns was present.

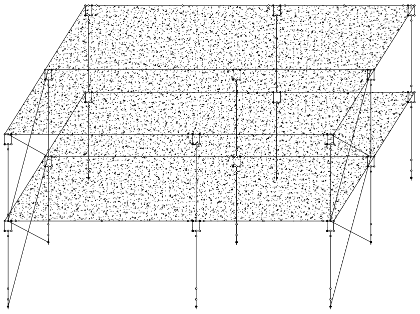

Fig. 15. The 3D FE model for dynamic identification

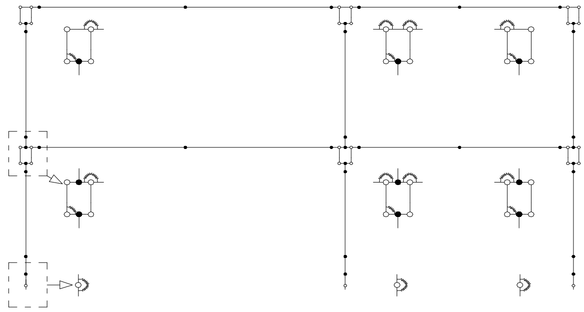

Fig. 16. Sketch of the interior frame of the 3D FE model for dynamic identification

Table 2. Identified frequencies and relevant error with respect to experimental data

Mode	Phase 1		Phase 2		Phase 3	
	Frequency [Hz]	Error	Frequency [Hz]	Error	Frequency [Hz]	Error
1	3.36	0.1%	2.33	2.2%	1.96	-0.4%
2	5.04	1.0%	4.63	-4.2%	4.20	-1.1%
3	7.02	-1.5%	6.44	-3.2%	5.80	-1.7%
4	11.51	-5.9%	9.69	-8.2%	8.45	-3.4%
5	15.45	6.3%	12.85	7.9%	11.91	16.0%

Table 3. Identified values of the element stiffness in the three test phases

Parameter	Element	Phase 1	Phase 2	Phase 3
p1	$EJ_{max,\ HEB260}$ [N m^2]	3.80E+07	3.76E+07	3.68E+07
	$EJ_{min,\ HEB260}$ [N m^2]	2.10E+07	2.04E+07	1.92E+07
	$GJ_{t,\ HEB260}$ [N m^2]	1.45E+07	1.43E+07	1.37E+07
	$EJ_{max,\ HEB280}$ [N m^2]	4.98E+07	4.93E+07	4.81E+07
	$EJ_{min,\ HEB280}$ [N m^2]	2.77E+07	2.69E+07	2.53E+07
	$GJ_{t,\ HEB280}$ [N m^2]	1.95E+07	1.91E+07	1.84E+07
p2	EA_{braces} [N]	2.78E+08	2.48E+08	1.93E+08
p3	$K_{\phi,\ interior\ connections}$ [N m/mrad]	1.02E+08	4.17E+07	3.19E+07
	$K_{\phi,\ exterior\ connections}$ [N m/mrad]	9.71E+07	3.30E+07	1.24E+07
	$K_{\phi,\ max,\ base\ joints}$ [N m/mrad]	2.07E+08	1.89E+07	1.36E+07
	$K_{\phi,\ min,\ base\ joints}$ [N m/mrad]	1.39E+08	1.27E+07	9.12E+06

Table 4. Diagonal MAC correlation coefficients between experimental and identified eigenvectors

Mode	Phase 1	Phase 2	Phase 3
1	1.00	0.99	0.95
2	1.00	1.00	1.00
3	0.78	0.84	0.81
4	0.96	0.98	0.83
5	0.82	0.87	0.79

Summary

Results of 2D and 3D finite element models, updated with cyclic static and dynamic test results, were presented and commented upon. Instrumental set-up was focussed at detecting the behaviour of beam-to-column joints, modelled as a set of rigid bars connected together by pins and rotational springs in order to dissipate seismic energy. Rotational data acquisition resulted more effective for static than dynamic tests. Modal rotation acquisition resulted particularly involved when evaluated by means of vertical accelerometers and when relevant to beam-to-column joints at the bottom storey in the second flexural mode.

The minimum search was performed by means of the robust non-linear Powell's Dog Leg optimization method, which provided a convergence to local minima faster and more reliable than damped Gauss-Newton method. Parameters were assigned to the flexural stiffnesses of beams and columns, respectively, and to the rotational stiffnesses of the joint components.

The cyclic identification permitted to update a consistent number of parameters, close to that of available measurements. The inelastic behaviour was detected by means of the secant stiffness approach, implementing a novel procedure based on the transferring of the reference system at each half cycle. As a result, the internal actions in the structure and the joint behaviour, in the form of moment-rotation diagrams were evaluated.

In the dynamic identification, a limited number of parameters compared to that of elements affecting the dynamic response i.e. braces, columns, beam-to-column and base joints, were updated. Therefore, all available information from static tests were employed and additional assumptions on structural components behaviour were imposed. Moreover, since the same parameter was applied to more than one structural elements, an averaged identification was necessarily obtained.

Requiring the solution of an inverse problem, static and dynamic model updating results appeared to be very sensible to available quality of experimental data.

Acknowledgments

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