

EXPERIMENTAL DYNAMIC ANALYSIS OF A STEEL STAIRCASE

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SUMMARY: This work presents the structural check, executed by means of free vibration tests, of a steel staircase of a concrete building, with no constraints with the building itself. Free vibrations have been generated by means of instantaneous release of the structure from a deformed configuration obtained by means of an imposed top structure horizontal displacement. The experimental tests have been executed by means of an hydraulic jack able to provide the traction force required by a suitable imposed horizontal displacement of the stair top level. The main purpose of the experimental tests is the structural dynamic parameter identification, such as natural frequencies, modal shapes and damping ratios. The modal parameters are identified by means of a time domain technique based on the Ibrahim's method. In the paper, beside the detailed description of the adopted test procedure, and the description of the identified modal parameters, their correlation with the results provided by a finite element model based on the design data, is also presented.

KEYWORDS: Identification, free vibrations, rapid release device.

INTRODUCTION

“In situ” tests by means of vibration methods are very effective procedures for the assessment of the dynamic behaviour of the structure [1,3]; moreover, often, under certain circumstances, they represent the only means able to provide basic information concerning structural aspects. In addition, they also allow the detection of anomalous behaviours connected to important structural aspects.

In this work the execution of free vibration tests of a steel staircase are presented. In particular, free vibrations have been obtained by means of instantaneous release of the staircase from a deformed configuration. A detailed description of the adopted device able to impose a horizontal displacement and allowing a subsequent instantaneous release is also presented. Moreover, a brief description of the device used for the acceleration measurements is provided together with the most significant recorded acceleration time histories.

Aim of the work is analysing the acceleration time histories by means of the time domain Ibrahim's method [6,7,8] in order to obtain the dynamic modal parameters. The obtained results are compared to those provided by a finite element model in order to assess the

reliability of the analytical model. The finite element model is updated by means a direct method [4] in order to obtain a valid model within the range of the identified modes.

DESCRIPTION OF THE STRUCTURE

The structure under study is a fire escape steel staircase of the new faculty of Agriculture of the University of Catania. The steel staircase has a triangular plan and it is developed along four levels up to a maximum height of about 15.30 m. A picture is reported in Fig. 1.



Fig. 1: Staircase under study

The staircase is supported by three main columns realised with HEA300 structural steel connected to each other at the top edge by means of three IPE300 structural steel and at bottom edge by means of UPN180 steel braces. The three main columns are clamped to the concrete foundation by means of stay bolts. The flights develop around the main structure and are constituted by UPN180 structural steel supporting the steps realised by means of 8 mm thick shaped chequered plate. IPE300 cantilevers clamped to the main columns at the foot-pace levels support the flights. For security reasons a rail along the entire height of the structure protects the staircase. Each connection between structural elements is bolted.

Table 1: Geometric characteristics of the steel staircase structural element

Profile type	J_t [cm ⁴]	I_x [cm ⁴]	I_y [cm ⁴]	A [cm ²]
HEA300	60.24	18263.00	6310.00	112.00
IPE300	15.57	8356.00	604.00	53.80
UPN80	1.91	106.00	19.40	11.00
UPN180	8.57	1350.00	114.00	28.00

IMPOSED DISPLACEMENT RAPID RELEASE DEVICE

The application of an imposed displacement to the structure requires a nearby element to be utilised as a contrast. In this specific case the main building of the Agriculture Faculty adjacent to the steel staircase (as shown in Fig. 1) has been adopted as contrast for a hydraulic jack. The latter is able to impose a displacement to the structure to be tested by means of a

high resistance cable. An edge of the cable is fixed to the staircase; the other edge is connected to the rapid release device, as shown in Fig. 2a. The hydraulic jack is hinged to a bolted wall plate clamped to the concrete building, as shown in Fig.2b, by means of heavy loads expansion dowels. The hydraulic jack provides a traction load to the staircase at the top level. This choice allows the imposition of the maximum strain energy for a given external load. It has to be pointed out that the non-destructive character of the test to be conducted implies no damage both at the staircase and the main building adopted as a contrast. To this purpose, particular care has been devoted to the calibration of the load to be applied in relation to the strength of the concrete wall of the building, to the strength of the anchorage plate, and to the elastic limit strength of the stair case structural steel.

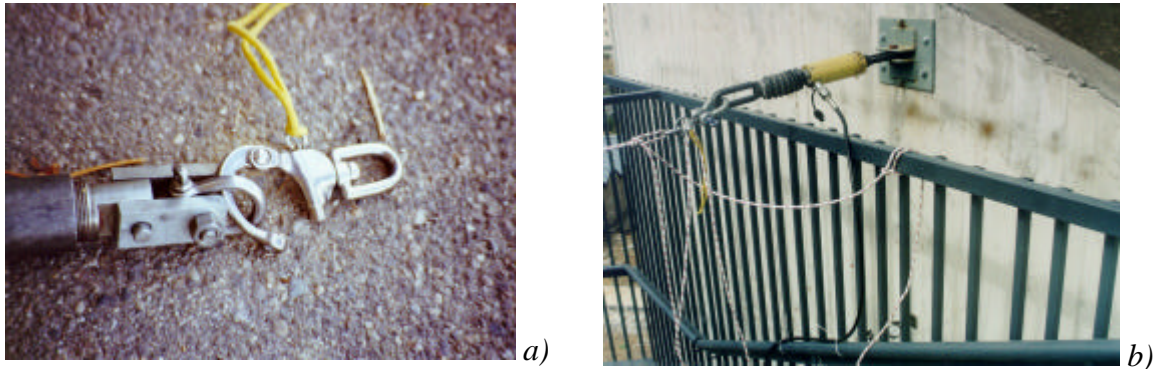


Fig. 2: a) A zoom view of the rapid release device, b) Collocation of the hydraulic jack

DESCRIPTION OF TESTING EQUIPMENT

Acceleration transducers (accelerometers), the data acquisition system and the rapid release device compose the testing equipment. Twelve capacitive type acceleration transducers, with $\pm 2g$ range of measurement and $0.5 V/g$ nominal sensitivity have been used. The transducers have been fixed to the staircase by means of application with cianoacrilatum instantaneous adhesive of a steel plate for each of them. The transducers have been connected to the alimentation and the acquisition console by means of screened multiple cables. In order to limit the noise due to vibration cables, the latter have been fixed to the staircase by means of plastic clips. An A/D converter with 12 bit PCMCIA gate and a portable PC, as shown in Fig. 3 compose the data acquisition system. The signals have been recorded by means of specific software able to interactively manage sampling frequency and length of registration.



Fig. 3: Dynamic data acquisition system

EXPERIMENTAL TESTS

Dynamic tests have been performed according to two different configurations strictly related to two different directions of the acceleration transducers. In the first configuration the transducers take the radial direction to the centre of the staircase. This configuration allows detection of the flexural behaviour components of the structure. In the second configuration, the acceleration transducers take the tangential direction able to capture the torsional behaviour components of the structure. In both configurations two different imposed displacement directions have been applied: radial displacement and tangential displacement. Table 2 summarises the types of tests that have been executed and indicates the abbreviation for each of them.

Table 2: Experimental set-up configurations

TEST	SET-UP 1		SET-UP 2	
	Accelerometer	Test name	Accelerometer	Test name
Radial displacement	Radial	RLR	Tangential	TLR
Tangential displacement	Radial	RLT	Tangential	TLT

The acceleration transducers are placed at the foot-pace levels near the main columns, and the two mentioned configurations are depicted in Fig. 4.

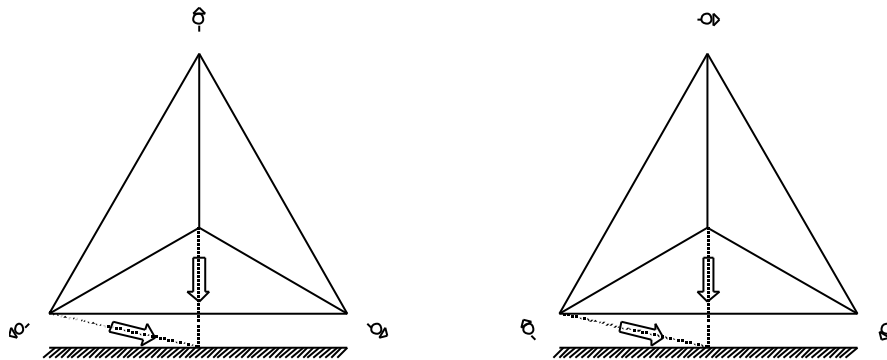


Fig. 4: Experimental set-up for the two test configurations

The details of a measurement station are reported in Fig.5. The steel plates to which the transducers are fixed along both radial and tangential directions can also be distinguished in Fig.5.

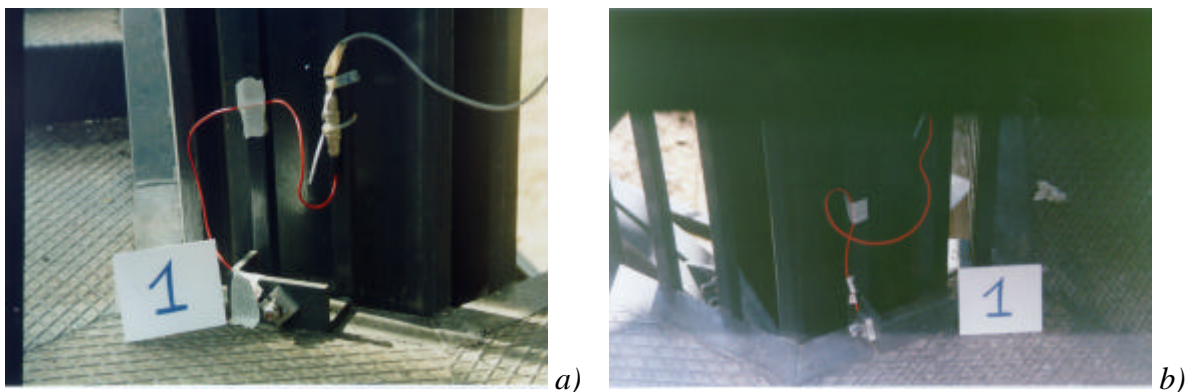


Fig. 5: Measurement station n. 1: a) Radial direction; b) Tangential direction

Acceleration time histories have been recorded with 500 Hz sampling frequency and for a 12 sec duration. In Fig. 6 two acceleration time histories regarding the radial and tangential directions are reported.

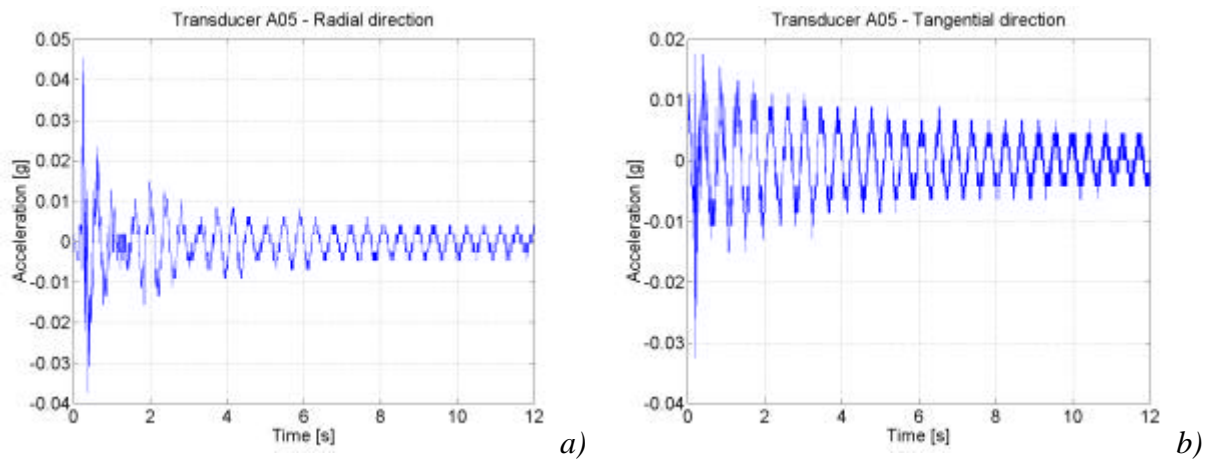


Fig. 6: Acceleration time history, transducer A05:
a) Radial direction; b) Tangential direction

MODAL PARAMETER IDENTIFICATION

Modal parameter identification has been conducted in time domain by making use of Ibrahim’s method [6,7,8] on the basis of the samples of the free vibration response histories. Ibrahim’s method is particularly effective since describes the noise components affecting the registrations as an additional signal characterised by specific frequencies, damping ratios and modal shapes to be identified. In the identification procedure, both the proper structural modes and those belonging to the environmental noise are evaluated. The latter will be referred to as “computational modes” throughout the paper. Proper structural modes will be distinguished from the computational modes according to the following parameters: MSCCF [2] (*Modal Shape Coherence and Confidence Factor*), MCF [5] (*Modal Confidence Factor*), MPC [4] (*Modal Phase Collinearity*) and MPD [4] (*Modal Phase Deviation*). In particular, structural modes have been recognised and selected according to the parameter values reported in the following table:

Table 3: Parameter limit values adopted for the identification

MSCCF Amplitude	MSCCF Phase	MCF Amplitude	MCF Phase	MCP	MPD
> 0.99	< 10°	> 0.99	< 10°	> 0.85	< 0.60

Furthermore, among all the identified modes, those with damping ratio greater than 20% have been discarded, since they do not correspond to real values for the structure under study.

The identification procedure has been applied for the radial direction and the tangential direction tests separately leading to natural frequencies, periods, damping ratios, modal shapes and identification parameters. In particular, frequencies, damping ratios, MSCCF parameter in terms of amplitude and phase, MCP and MPD parameters, for three tests are reported in the following tables (Table 4, RLR – set-up; Table 5, TLR – set-up; Table 6, RLT – set-up; Table 7, TLT – set-up):

Table 4: Accelerometers in radial direction with imposed radial displacement

SET-UP RLR	Frequency [Hz]	Period [s]	Damping ratio [%]	MSCCF Amplitude	MSCCF Phase [°]	MCP	MPD
1° frequency							
Test 1	2.274	0.440	1.230	0.995	-0.167	0.985	0.565
Test 2	2.298	0.435	0.688	0.999	-0.439	0.991	0.142
Test 3	2.296	0.436	4.464	0.998	-0.137	0.970	0.215
Mean	2.289	0.437	0.794				
Var. [%]	0.488	0.482	40.537				
2° frequency							
Test 1	2.748	0.364	2.974	0.994	0.274	0.999	0.053
Test 2	2.774	0.360	3.257	0.990	0.417	0.998	0.065
Test 3	2.765	0.362	3.091	0.990	-0.018	0.997	0.060
Mean	2.762	0.362	3.107				
Var. [%]	0.388	0.399	0.734				

Table 5: Accelerometers in tangential direction with imposed radial displacement

SET-UP TLR	Frequency [Hz]	Period [s]	Damping ratio [%]	MSCCF Amplitude	MSCCF Phase [°]	MCP	MPD
1° frequency							
Test 1	2.288	0.437	0.998	0.996	-0.162	0.989	0.135
Test 2	2.284	0.438	3.321	0.999	0.134	0.992	0.119
Test 3	2.302	0.435	1.714	0.980	0.338	0.993	0.161
Mean	2.291	0.437	2.011				
Var. [%]	0.331	0.329	48.308				
3° frequency							
Test 1	3.165	0.316	3.130	0.991	-0.125	0.979	0.154
Test 2	3.048	0.328	2.776	0.992	0.080	0.998	0.062
Test 3	3.037	0.329	2.584	0.996	-0.493	0.989	0.180
Mean	3.083	0.324	2.830				
Var. [%]	1.877	1.851	7.996				

Table 6: Accelerometers in radial direction with imposed tangential displacement

SET-UP RLT	Frequency [Hz]	Period [s]	Damping ratio [%]	MSCCF Amplitude	MSCCF Phase [°]	MCP	MPD
1° frequency							
Test 1	2.284	0.438	0.917	0.996	0.009	0.996	0.217
Test 2	2.308	0.433	0.231	0.999	0.002	0.999	0.066
Test 3	2.307	0.433	1.094	0.997	0.119	0.997	0.106
Mean	2.300	0.435	0.747				
Var. [%]	0.481	0.488	49.819				
2° frequency							
Test 1	2.827	0.354	1.723	0.995	0.139	0.999	0.039
Test 2	2.958	0.338	1.782	0.997	0.034	0.999	0.040
Test 3	2.776	0.360	2.893	0.998	0.328	0.999	0.056
Mean	2.854	0.351	2.133				
Var. [%]	2.677	2.645	25.234				

Table 7: Accelerometers in tangential direction with imposed tangential displacement

SET-UP TLT	Frequency [Hz]	Period [s]	Damping ratio [%]	MSCCF Amplitude	MSCCF Phase [°]	MCP	MPD
1° frequency							
Test 1	2.291	0.436	1.475	0.994	-0.094	0.996	0.114
Test 2	2.291	0.437	2.284	0.996	0.275	0.994	0.110
Test 3	2.274	0.440	1.282	0.999	0.132	0.997	0.141
Mean	2.285	0.438	1.681				
Var. [%]	0.347	0.350	25.828				
3° frequency							
Test 1	3.189	0.314	2.595	0.992	0.040	0.999	0.032
Test 2	3.146	0.318	2.695	0.992	0.086	0.999	0.065
Test 3	3.063	0.327	2.374	0.994	0.122	0.999	0.090
Mean	3.133	0.319	2.555				
Var. [%]	1.666	1.679	5.249				

For each experimental set-up the mean values of frequencies, periods and damping ratios together with the variation coefficient, obtained as the ratio between the standard deviation and the mean value, are also reported in Tables 4-7.

The above mentioned results obtained for different set-ups have been interpreted in order to recognise the first three structural modes and are summarised in Table 8.

Table 8: Identified modal parameters: modal frequency and damping ratio

TEST Mode	Radial displacement			Tangential displacement		
	RLR	TLR	Mean value	RLT	TLT	Mean value
1	2.289 Hz 0.794%	2.291 Hz 2.011%	2.290 Hz 1.403%	2.300 Hz 0.747%	2.285 Hz 1.681%	2.293 Hz 1.214%
2	2.762 Hz 3.107%	-	2.762 Hz 3.107%	2.854 Hz 2.133%	-	2.854 Hz 2.133%
3	-	3.083 Hz 2.830%	3.083 Hz 2.830%	-	3.133 Hz 2.555%	3.133 Hz 2.555%

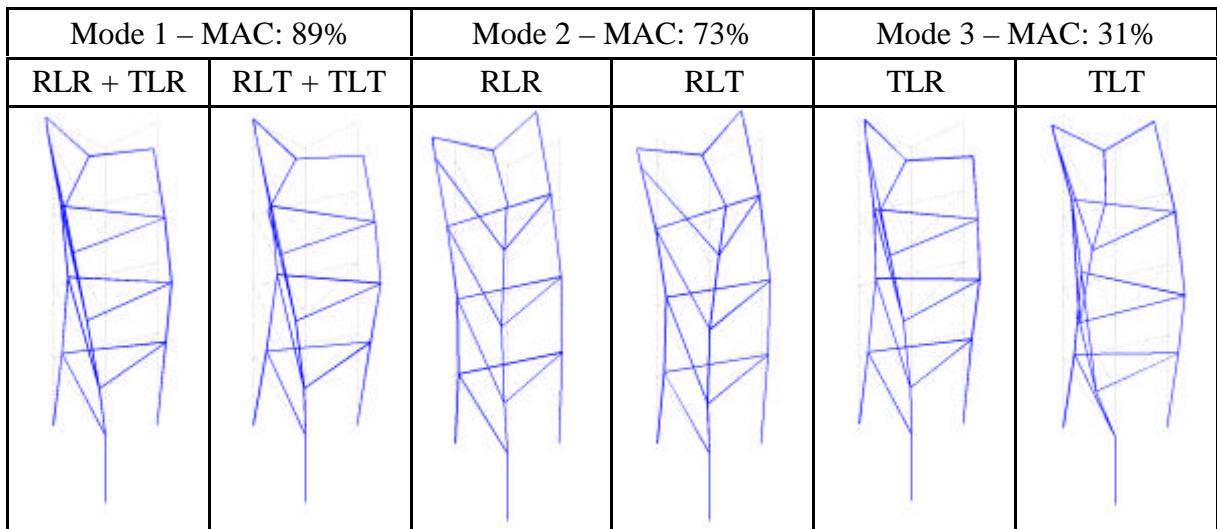


Fig. 7: Identified modal shapes in radial and tangential accelerometer configurations

The identified modal shapes are reported in Fig. 7. The identified modal shapes for imposed radial and tangential displacement have been compared by means of the Modal Assurance Criterion, MAC [1] and the MAC values are reported at the top of Fig. 7. In particular, it has to be remarked that modal shapes have been obtained as suitable expansions [4] of the strictly identified shapes to the degrees of freedom of the subsequently adopted analytical model.

FINITE ELEMENT MODEL

The structure has been discretized by means of a finite element model as shown in Fig.8. Mono-dimensional frame elements have been adopted, and nodes have been considered where connections between the flights and the main structure are present.

The geometrical characteristics of each element are reported in Table 1 and the Young modulus has been assumed $2.1 \times 10^{11} \text{ N m}^{-2}$. In order to take into account the masses of the protection rail, of the steps and of the secondary beams, additional concentrated masses of 408 kg have been considered at the nodes. The torsional and flexural stiffness of the main structural elements have been incremented to account for the presence of the rail. The modal characteristics in terms of undamped natural frequencies together with the relative modal shapes of the analytical model are reported in Fig. 8.

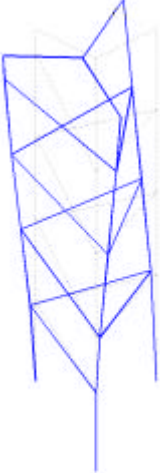
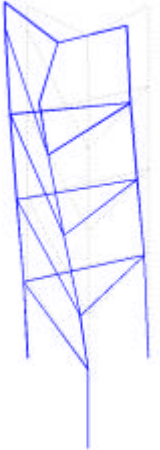
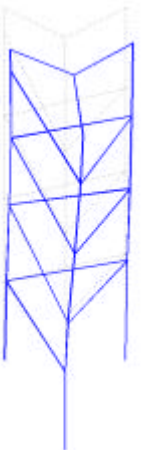
Mode 1 – $f_1 = 2.095 \text{ Hz}$	Mode 2 – $f_2 = 2.727 \text{ Hz}$	Mode 3 – $f_3 = 3.134 \text{ Hz}$
		

Fig. 8: Modal shape of designed finite element model

FINITE ELEMENT MODEL UPDATING

The identified modal parameters have been used to update the finite element model by means of a direct correction method able to provide a single step optimisation of the analytical system matrices. More precisely, the direct correction method using Lagrange multipliers [4] minimising a weighted distance between updated and original mass and stiffness matrices under orthogonality conditions has been adopted.

The correlation level between the original model, the updated model and the results of the test has been evaluated by comparing the first three natural frequencies. In Table 9 the identified frequencies, the designed and updated finite element model frequencies and the relative errors are reported. Furthermore, the global correlation level has been determined by means of the global frequency error evaluated by making use of the following relationship, Eqn 1:

$$GE \% = \sqrt{\frac{\sum_{i=1}^3 (f_i^{FE} - f_i^{ID})^2}{\sum_{i=1}^3 (f_i^{ID})^2}} \times 100 \quad (1)$$

Table 9: Frequency correlation between designed, updated and identified model

Mode	FE [Hz]	Identified model frequency				Updated FE model frequency			
		Radial [Hz]	Err. [%]	Tangential [Hz]	Err. [%]	Radial [Hz]	Err. [%]	Tangential [Hz]	Err. [%]
1	2.095	2.290	-8.53	2.293	-8.65	2.290	0.00	2.293	0.00
2	2.727	2.762	-1.28	2.854	-4.46	2.762	0.00	2.854	0.00
3	3.135	3.083	1.68	3.133	0.05	3.083	0.00	3.133	0.00
GE [%]			4.34		4.89		0.00		0.00

Moreover, the identified modal shapes and the designed finite element modal shapes have been compared by means of the Modal Assurance Criterion. The obtained correlation is very low and the relative MAC coefficient matrix is reported in Fig.9.

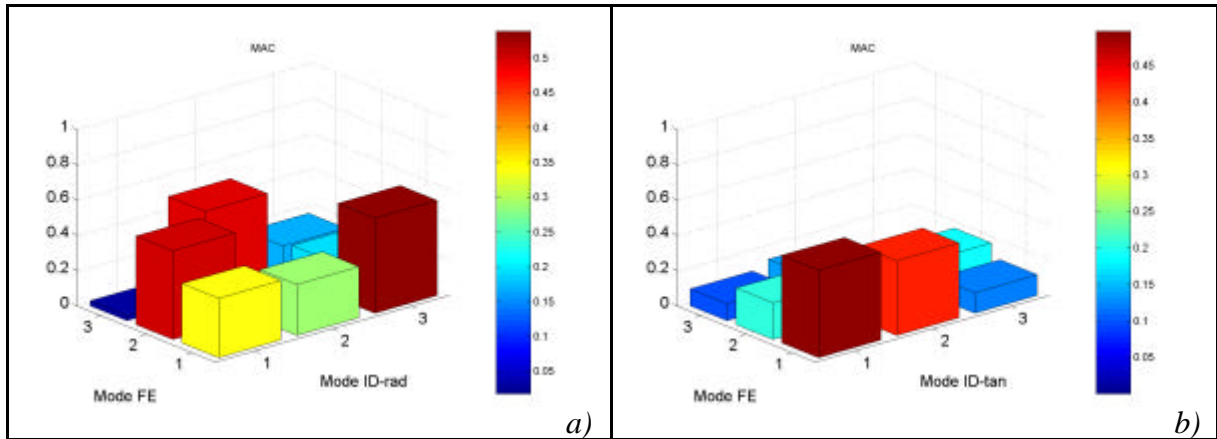


Fig. 9: Correlation between modal shape identified and shape of designed finite element model: a) radial displacement test; b) tangential displacement test

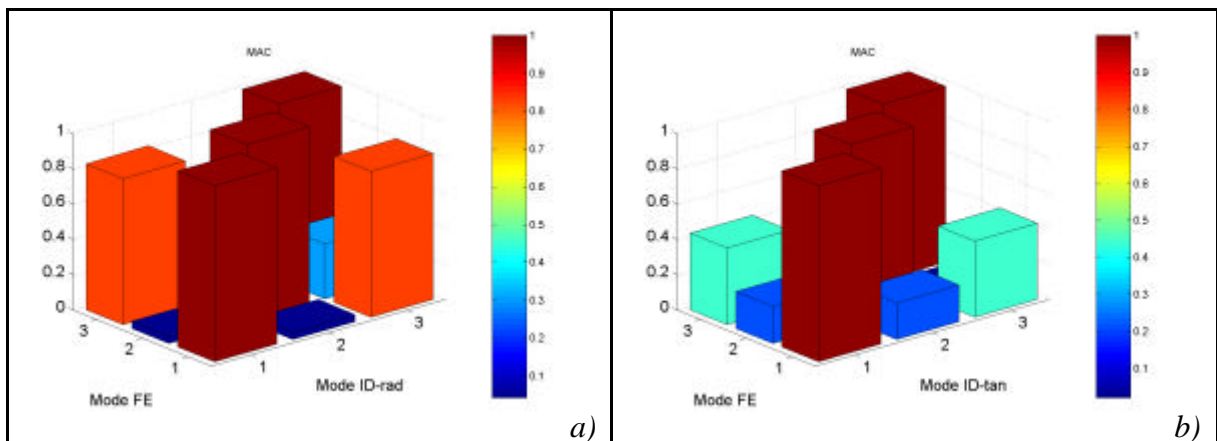


Fig. 10: Correlation between modal shape identified and shape of finite element model updated: a) radial displacement test; b) tangential displacement test

However the correlation improves drastically whenever the Modal Assurance Criterion between the identified and the updated finite element modal shapes is applied, as shown by the MAC coefficient matrix reported in Fig. 10

CONCLUSIONS

In this work dynamic tests for the identification of the modal parameters of a steel staircase have been presented. The tests have been performed by means of a hydraulic jack and a rapid release device allowing the imposition of initial displacements with easy and quick repetitions. The system response has been analysed by means of a time domain identification procedure due to Ibrahim and the first three natural modes of the structure have been obtained. Particular attention has been devoted to the interpretation of the results concerning different test set-ups. The identified parameters have been initially compared with the modal parameters of an analytical model formulated according to the classical finite element technique on the basis of estimated system parameters. Since a low accuracy of the model has been encountered a system matrix direct updating procedure has been applied to the finite element model in order to improve the modal frequency and shape correlation.

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