Dynamic Identification of All-FRP Pultruded Structures

G. Boscato, A. Dal Cin, and S. Russo

***Abstract*—The first experimental dynamic parameters of a large spatial FRPs (Fiber Reinforced Polymers) pultruded structures are presented in this research. This construction is a temporary structure realized to accommodate future restoration work and to cover a historic church of Santa Maria Paganica stroked and partially collapsed by 2009 L'Aquila earthquake. The covering structure is an all FRP spatial-reticular with elements made by pultrusion process, connection plates by bag molding process and steel bolts. The dynamic behavior was analyzed using the ambient vibrations test to measure the mode of vibration, frequencies, displacements and damping ratios of the structures using a modal identification of output-only systems. The operational modal analysis OMA has been carried out to identify the modal characteristics through poly-reference Least Square Complex Frequency-domain (pLSFC) estimator.**

***Index Terms*—All-FRP structures, dynamic parameters, ambient vibrations test, modal identification.**

I. Introduction

The aspects have not yet been investigated of pultrusion technology concern the dynamic parameters. The limited knowledge in dynamic field penalizes the employment of all-FRP structure in seismic zones.

In fact, the use of composite fiber reinforced frames was widely tackled in its static aspects [1]-[4], on the contrary, there is again less information about its dynamic characterization [5]-[14]. However some early information on the structural response with respect to these actions had been already published [15]-[17].

This study takes advantage of the availability of one of the biggest PFRP frames in Italy [18].

The well known tested structure [18], was built in order to temporarily protect the church of Santa Maria Paganica in L'Aquila that was badly damaged during the 2009 earthquake.

Modal identification techniques are used to estimate the dynamic properties of a structure based on experimental data. This technique has gained significant importance in the last two decades because it is an important step for model updating techniques, structural health monitoring [19]-[20] and damage prognosis in particular after the seismic events. For structural characterization the operational modal analysis OMA, that in civil engineering field is well known as "ambient response" testing, forms the only available technique to identify the large structure. These cases are difficult to test using traditional methods involving known excitation. In OMA approach the unknown environmental loads (traffic, wind and waves) - that for the traditional techniques the background noise becomes a problem - are used as the basis of the testing and subsequent modal analysis [21]. The capability of OMA is widely proved for complex congiguration where non-obtrusive approach and global assessment are necessary. Several researches have been addressed on structural identification of cultural heritage using ambient vibration data [22]. For the structural control and health monitoring long term - considering the structural identification and the safety measures activities - of an historic building damaged by earthquake a static and dynamic system was adopted [23]-[24].

By applying the output-only technique with the sole input of earthquake-induced vibration, the main mode shapes were determined, together with their frequency and the damping ratio.

The experimental dynamic parameters that were obtained can be used to calibrate a finite element model by using the model updating process in order to evaluate the dissipative capacity of the structures.

II. General Description

The complete structure allows to test its two types of frames, the lower one (named structure 1) and the higher one (structure 2), both with concentric V bracing and with active tension diagonal bracings.

The pictures in Fig. 1 show structures 1 (low) and 2 (high) made by pultruded profiles and steel bolts which are the object of this study; Fig. 1a represents the whole view while Fig. 1b and c shows the two structures in detail.

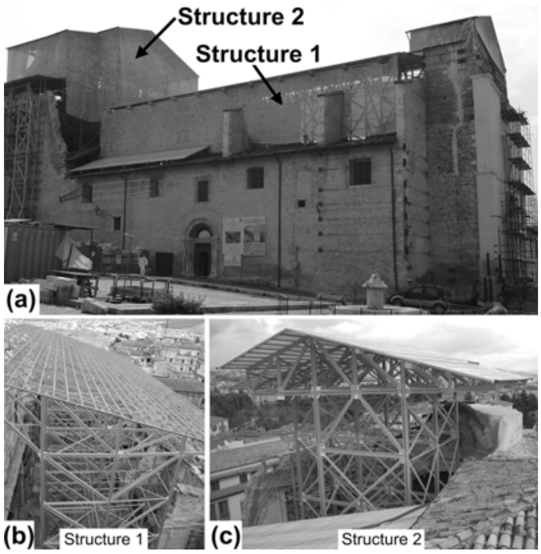

Fig. 1. View of all-PFRP structures.

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Fig. 2 shows the plan of the structures inside the church of Santa Maria Paganica and the framework they are made of, detailed in Fig. 3 and Fig. 4, indicated with the letters from *a* to *q*. For framework from *g* to *m* of structure 1, the roofing has been elongated (see asterisks of Fig. 2) in order to reach the perimeter masonry walls.

With reference to Fig. 2, structure 1 (Fig. 1b) stretches for 607 m^2 above the nave and reaches a maximum height of 22.5 m. Structure 2 (Fig. 1b) shelters the apse zone being 266 m^2 large and 29.4 m high.

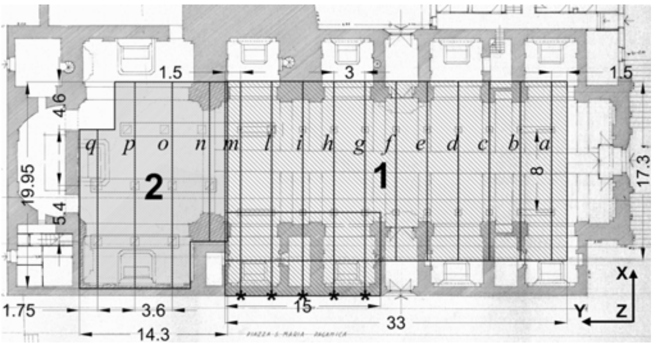

Fig. 2. PFRP structures inside the church (dimensions in meters).

Fig. 3 and Fig. 4 show the details of the frames with reinforced concrete foundation blocks linked to one another. Each structural member is denoted by an abbreviation that indicates the number of assembled profiles (e.g. 4Cs is for four C profiles, 2L is for two angular profiles) and their cross-section dimensions in millimeters.

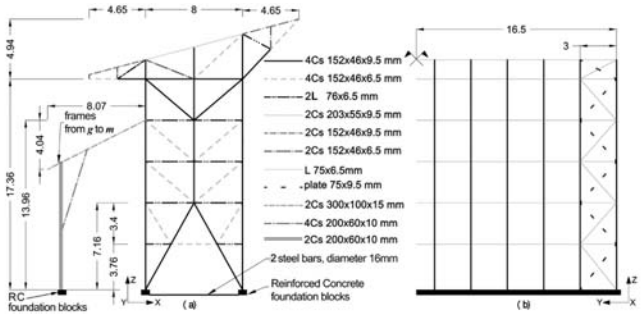

Fig. 3. Structure 1; front view (a) and side view (b), dimensions in meters.

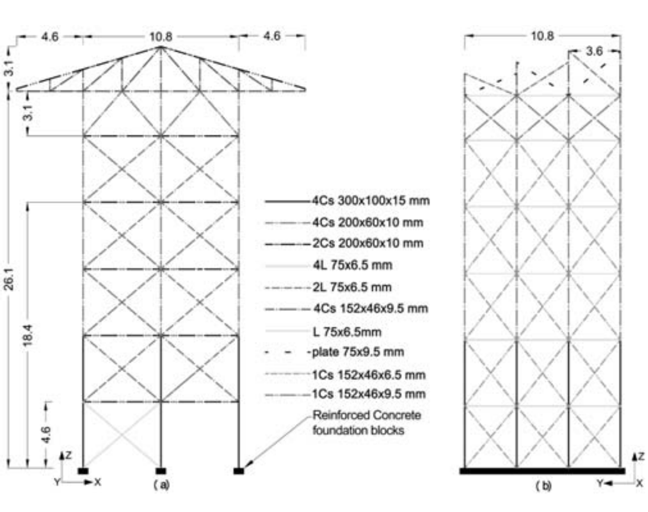

Fig. 4. Structure 2; front view (a) and side view (b), dimensions in meters.

The structure with simply supported base constraints was designed against the typical seismic actions, of the site of L'Aquila, taking into account the high vulnerability to local buckling phenomena [25]-[27].

The mechanical properties of the pultruded profiles employed are listed in Table I. In particular, subscribed *z* denotes the vertical axis of the profile, while *x* and *y* define the cross-section plane.

TABLE I: MECHANICAL PROPERTIES OF THE PFRPS PROFILES, EXPERIMENTAL DATA.

Mechanical properties	Symbol	Value
Longitudinal tensile strength	σ_Z	350 MPa
Transversal tensile strength	$\sigma_X = \sigma_Y$	70 MPa
Longitudinal elastic modulus	$E_Z = E_L$	24.4 GPa
Transversal elastic modulus	$E_X = E_Y = E_T$	9 GPa
Shear modulus	$G_{XY} = G_T$	3.6 GPa
Shear modulus	$G_{ZX} = G_{ZY} = G_{LT}$	3.2 GPa
Poisson's ratio	$\nu_{ZX} = \nu_{ZY} = \nu_{LT}$	0.23
Poisson's ratio	$\nu_{XY} = \nu_T$	0.09
Density	γ	1850 kg/m^3
Fibres percentage	V_f	48%

III. MODAL ANALYSIS

In order to choose the most correct settings and procedure for dynamic identification, a preliminary FEM modal analysis was run on the whole structure by means of the calculation code Strand 7. Fig. 5 shows the model consisting of 1725 beam elements and 481 connections regarded as rigid nodes.

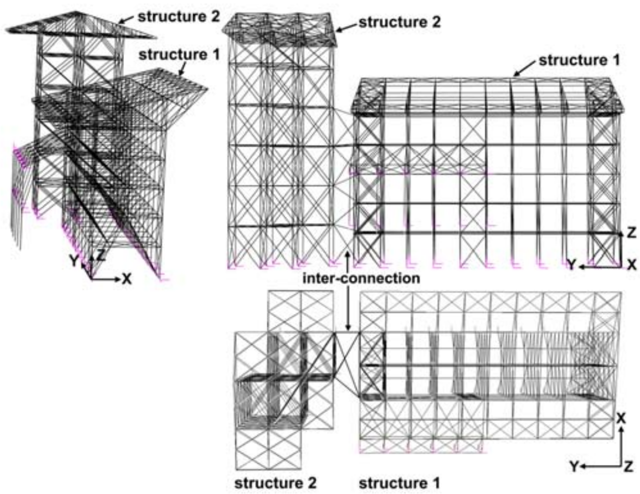

Fig. 5. General views of the FEM model for structures 1 and 2.

Table II reports the percentages of participating mass activated along *X*, *Y* and *Z* axis and around the same (*RX*, *RY* and RZ) for each vibration mode, the grey cells enlighten the maximum values.

TABLE II: VIBRATION MODES AND PARTICIPATING MASS, FEM

Modes	Hz	*X*	*Y*	*Z*	*RX*	*RY*	*RZ*
1	*2.23*	0%	86%	0%	51%	0%	2%
2	3.20	11%	5%	0%	8%	16%	1%
3	*3.31*	4%	3%	0%	3%	6%	22%
4	*3.85*	37%	3%	0%	3%	44%	2%
5	*4.18*	33%	0%	0%	0%	27%	60%

IV. Dynamic Identification

The project for the experimental identification provides dynamic control of the all structure (Fig. 2) to involve the entire distribution of mass and stiffness of the structure.

To obtain reliable outcomes a dynamic monitoring program was planned, with 52 measuring points and 4 schemes of acquisition, that are described here below (Fig. 6).

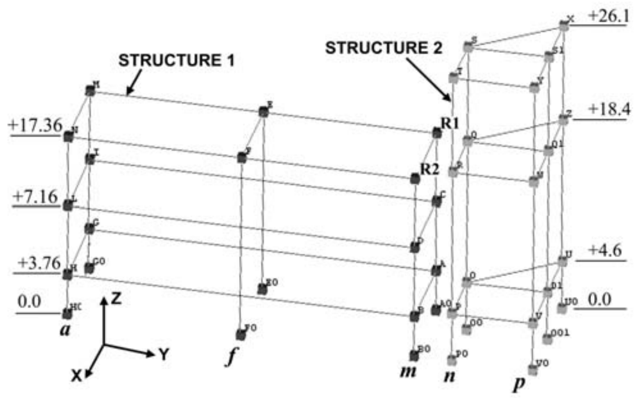

Fig. 6. Localization of the sensors in the structure.

The bi-axial accelerometers were put on three frames of structure 1(low) - named *a*, *f* and *m* - and on two frames of structure 2 (high), named *n* and *p*, see Fig. 2. On the whole, 48 accelerometric directions were set or frame *a*, *m*, *n* and *p*; while for frame *f* two bi-axial sensors, corresponding to 4 directions and thus 4 acquisition channels, were employed. Among the 52 accelerometric directions, the check points R1 and R2 in both directions each one, that lie on frame *m*, are regarded as fixed references; they allow to establish relationship among the 4 schemes of acquisition that involve the five frames, by means of a scaling process. Fig. 10a shows the monitored points, named A to N on structure 1, P to Z on structure 2, while R1 and R2 are the fixed ones.

For each acquisition channel, the measurements were taken with a sampling frequency of 200 Hz, with a suitable analog anti-aliasing filter and related 100 Hz band pass, that is one order of magnitude upper than the frequencies of interest previously esteemed via FEM analysis (Table II). The measurement equipment was completed by two 8-channels acquisition units, which worked independently from each other and were synchronized by means of GPS.

The measurements were taken while the structures were excited by ambient vibrations.

From the time history of each channel, that covered an acquisition time of about 1 hour, the structural response data were extracted with reference to each of the 4 acquisition schemes.

V. Experimental Results

For ambient vibration measurement with unknown inputs, the PolyMAX estimator, is proposed. The implementation of the frequency-domain Linear Least squares estimators, optimized for the application of a fast-stabilizing frequency domain parameter estimation method, is called Least Squares Complex Frequency –domain (LSCF) estimator, [28].

The stabilization diagram is considered the most common tool to select the physical poles. In this diagram (Fig. 7 and Fig. 8), the resonance frequency of the identified poles is visualized for different model orders.

The frequency is represented on the horizontal axis and in the vertical axis in the right side there is the polynomial degree used as a basis from which are extracted the modal parameters; the vertical axis shows the model order for which the poles are identified.

A symbol is associated to each pole corresponding to the degree of stabilization of the pole when compared to the analysis at the previous model order. The “o” corresponds to a new pole, the “f” indicates that the frequency of the pole is close to the one of the previous analysis, the “d” implies that also the damping has stabilized and the “s” corresponds to a pole that is stable in the frequency and damping (Fig. 7 and 8).

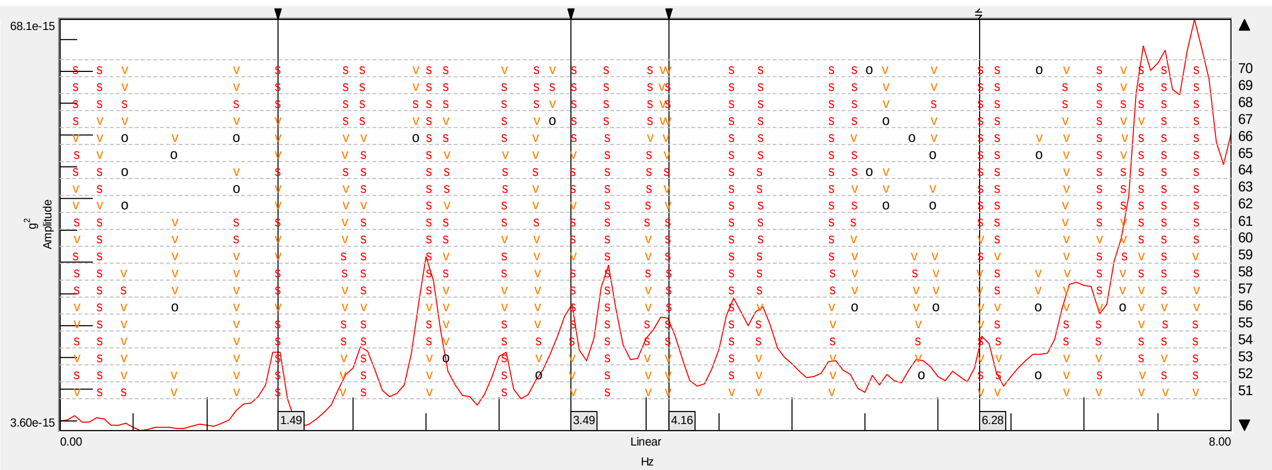

Fig. 7. Structure 1, Stabilization diagram of crosspower sum function, reference channel C.

From the diagram of stabilization of crosspower spectra previously calculated, were derived the main first modes of vibration and the corresponding damping.

The mode shapes and respective parameters, as frequency (Hz) and damping (ζ) for *X* and directions, are listed below in Fig. 9 and Fig. 10, respectively for structures 1 and 2.

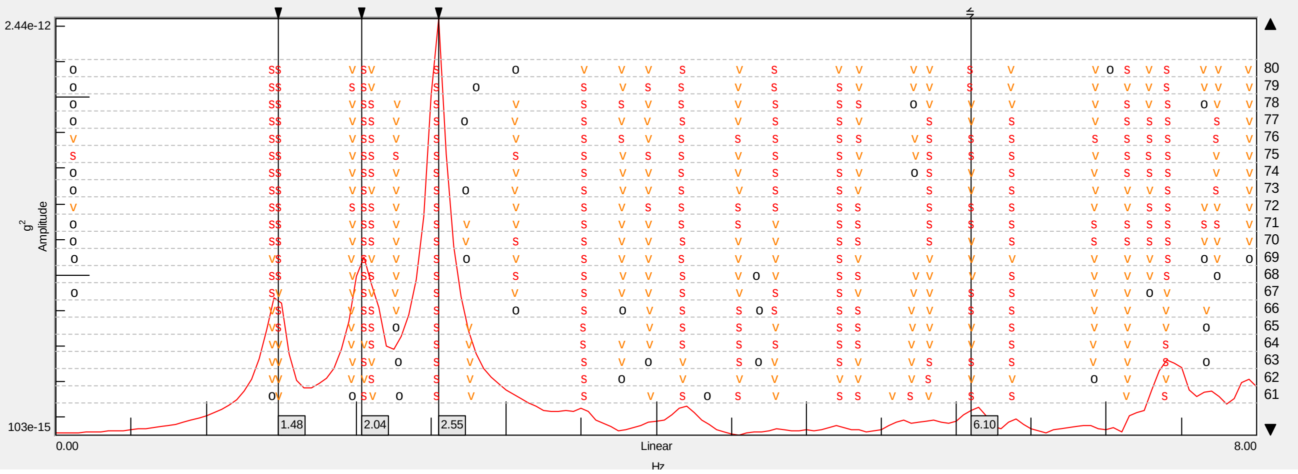

Fig. 8. Structure 2, Stabilization diagram of crosspower sum function, reference channel O.

It can be noticed that the first vibration mode of the two structures happens at the same frequency along Y axis (i.e. 1.48Hz for structure 1 and 1.49Hz for structure 2), while there is a variation of 5% along *X* axis (2.06Hz for structure 1 and 1.95Hz for structure 2). The second (3.49 Hz) and third mode shape (4.17 Hz) of structure 1 (low) correspond to torque vibration modes. Structure 2 shows a similar behavior, with second modal shape at 2.04 Hz; the third shape at 2.54 Hz and fourth at 6.15 Hz have a significant torque component. Except for the first mode, the independent behavior of the two structures can be seen.

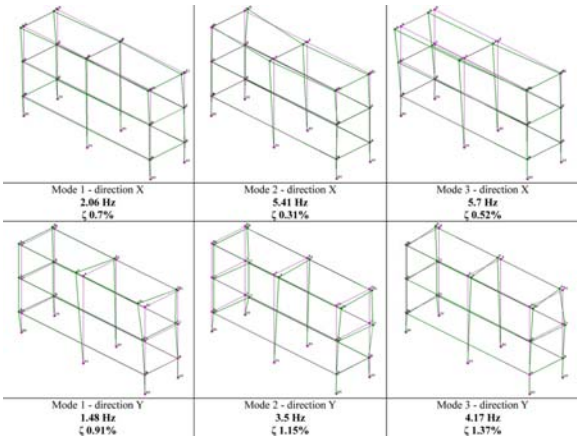

Fig. 9. First mode shape of the structure 1.

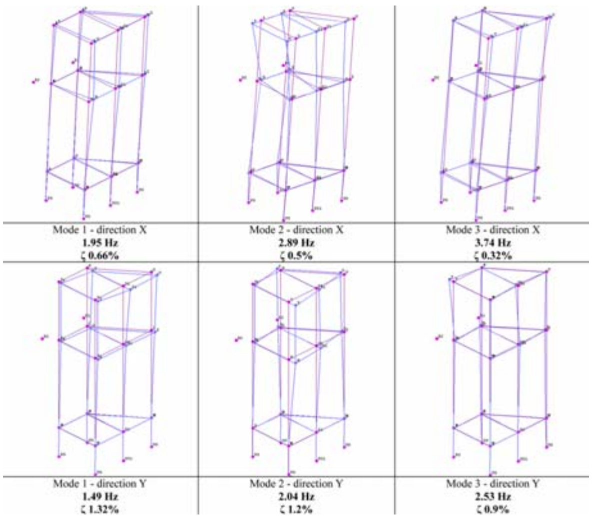

Fig. 10. First mode shape of the structure 2.

VI. Conclusions

Through the experimental results the following evaluations can be drawn: -the FEA outcomes point out a very stiff structure probably due to an over-dimensioning in absence of specific code. In detail the first mode period of 0.45 s involves the 86% of the mass along the Y axis and 51% along the X axis. The second mode, with a vibration period of 0.31 s, can excite the 11% of the mass along the transversal direction of the church (X axis); the third mode is of torque type with a period of 0.30 s; the fourth mode involves mainly the Y direction and finally the fifth is mainly of rotational type; - the operational modal analysis carried on with the sole input of ambient vibrations was found reliable and effective also in presence of structure made of FRP; - with reference to the dynamic identification the longitudinal axis coincides with the main direction of the first modal shape that happens at the same frequency for both the structures. Along the transversal *X* axis, the modes have higher frequencies than along the *Y* direction. The following modes are mainly of torque type, since they are affected by the side constraint to the church's wall; - more generally, the first mode frequency of 1.48 Hz with the damping coefficient $\zeta<1.3$ confirms the tendency of truss PFRP structures to low mode frequencies.

The experimental results dealt in this paper are the base to apply the model updating procedure. The calibrated model will allow to simulate different configurations in order to calculate the dissipative capacity of all-FRP pultruded structures.

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