EXPERIMENTAL SEISMIC VERIFICATION OF ASSEMBLED PREFABRICATED STRUCTURES

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SUMMARY

The experimental approach to the analysis of the dynamic behaviour of prefabricated structures may follow two different ways: the study of the dynamic behaviour of single structural elements tested separately, or the direct determination of the dynamic response of an assembled structure. In the opinion of the authors, the second procedure is preferable, since it by-passes the difficulties encountered in transferring to the assemblies the results obtained on single elements, in dealing with non-linearities and in taking into account the influence of the assembling operations.

After a discussion on these subjects, the paper illustrates the results of dynamic tests of some prefabricated assembled structures.

INTRODUCTION

Experimental analysis in civil engineering has usually two main purposes: to contribute to the solution of theoretical and technical problems during the design stage, and to provide a verification (and possibly, a qualification) of the characteristics of specimens or prototypes after construction. Both these aspects are of particular importance for prefabricated structures, since the theoretical, technical and economical considerations which call for the performing of an experimental analysis (in particular in the dynamic and seismic field) have a larger influence when dealing with this type of constructions than with the traditional ones. Suffice it to mention, to underline the theoretical considerations, the wide range of structural types and systems being used, usually of new concept and often making use of new and/or heterogeneous materials. As far as the technical aspects are concerned, differences may arise - for instance - as to the actual efficiency of joints or connections between the single precast elements, with respect to that assumed for design purposes, owing mainly to the assembling and mounting procedures. Moreover, it is not be disregarded that an industrialized building process requires, for obvious economic reasons, the optimization of the design, of the structural details and of the construction procedures, in order to reduce both the costs of materials and the assembling time.

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All these aspects pose a number of problems difficult to solve via analytical techniques solely; whereas they can be reliably dealt with if proper experimental procedures are adopted.

TESTING OF PREFABRICATED ELEMENTS AND STRUCTURES

Actually, static, quasi-static, cyclic and dynamic tests on prefabricated elements have been carried out for a long time. The related technical literature reports on a wide range of tests on different types of single structural elements for panel structures (panels, slabs, vertical and horizontal junctions) and for framed structures (beam-column joints, infilled walls, shear walls, etc.), carried out with the aim of determining their performance under static, dynamic and seismic loadings. These tests have provided a very large number of data on the behaviour of the structural elements, and have been successful in clarifying many aspects of the various problems under study.

However, the tests on single structural elements, which essentially supply the basic data for a verification of the analytical schematizations adopted by the designer, cannot provide the complete solution to the problem of the seismic performance of an assembled structure. On this matter, a reliable assessment can be made only if the overall seismic behaviour is determined, by means of proper dynamic tests on the complete structure or on an assembly of single parts which reproduce, in any case, its main characteristics.

The following considerations justify the carrying out of these tests:

- the behaviour of single elements or constructive details may not be compared to that of the same parts in the assembly, owing to different assembling procedures or conditions (differences in tightening of connection bolts, different shrinkage of cast-in-situ parts, effect of grouting, etc.);

- the actual load distribution on the assembled elements does not correspond to the simple schematizations usually adopted for tests of single elements;

- non-linearities in the behaviour of the elements are not easily handled by analytical procedures, and it is difficult to evaluate their influence on the overall behaviour;

- the present testing, measuring and processing techniques make it possible to carry out reliable and exhaustive seismic experimental analysis of the whole assembly, which allows its safety coefficient to be assessed and - at the same time - the actual behaviour of the single elements to be inspected: consequently, possible weak points of the project can be detected and information on how to improve it can be obtained.

TESTING PROCEDURE

Owing to the large variety of design concepts, structural details and assembling procedures, it is not possible to offer general criteria as to the testing methods, which have to be carefully chosen taking into account not only the particular structural design, but also the specific aims of the experimental investigation.

The testing method, which has been successfully adopted by ISMES in various cases, requires the dynamic excitation of the assembled prototype by means of a mechanical vibration generator, which applies to the structure horizontal sinusoidal forces of known intensity and variable frequency in the seismic range. The overall response of the structure is usually picked-up by means of an array of accelerometers, suitably placed on the structure in such a manner as to make up a sufficiently dense network. This facilitates the determination of the characteristics of the first vibration modes, starting from the transfer functions between the response and the applied force. The measurement of the response of structural elements or details is carried out so as to determine, if required, both kinematic quantities, such as displacements of joints, rotations of connections, etc., and the loadings (axial and shear forces, bending moments and torques) transmitted to such elements by the other parts of the structure. These measurements are made by means of strain gauges, displacement transducers, clinometers, etc.

The following examples, which refer to the tests carried out on two assembled structures with rather different structural configuration and assembling criteria, show in detail some of the interesting results that the experimental procedures can achieve.

TESTS ON A BOX STRUCTURE

The box structure tested is a two floor single family housing unit made up of trihedral elements (two orthogonal walls and floor) and horizontal rectangular slabs (fig. 1). The vertical elements are tightened by post-tensioned steel tendons, whereas the horizontal ones are connected by means of small metallic plates, welded together in situ. The aims of the test, which have been carried out on the building site (near the epicenter of the Friuli earthquake of 1976), were the following:

- to qualify the structure according to the requirements of the Italian earthquake regulations;
- to check the influence on the dynamic behaviour of the grouting of the connections as well as of the tendon ducts;
- to determine the strains, and thence the stresses, in the vertical cables and in the steel plates connecting the horizontal elements.

To this end, 48 accelerometers were mounted on the structure, 12 single strain gauges placed on six of the twelve tendons, and 14 three component rosettes on the 14 steel connections. The building was made to vibrate by a vibrodyne in the frequency range between 0 and 18 Hz; two series of tests were made: the first before grouting, the second after grouting. The tests made it possible to determine the notable influence of grouting on the dynamic behaviour (fig. 2), not only as far as the natural frequencies and amplifications are concerned, but also in making the structure monolithic. They also showed that all the connections were over-sized; and, thanks to the determination of two vibration modes in the seismic range (one of flexural type, the second of torsional type) made it possible to compute the response to the Italian code earthquake and to the main shocks of the Friuli earthquake.

It has to be underlined that, during the tests, many points of the structure experienced, in resonance conditions, maximum acceleration higher than 0.4 g lasting for several minutes, with no damage.

TESTS ON A FRAMED STRUCTURE WITH BOLTED JOINTS

The second example refers to a framed structure obtained by the assembly of reinforced concrete prismatic elements (fig. 3). The connections between the columns and the principal beams were obtained by bolting in situ these elements by means of four bolts per junction. The floors were made up of secondary beams fixed to the principal ones; external and partition walls are mounted after the construction of the frame, and do not have structural functions.

The main purpose of the tests - besides, of course, the analysis of the structural response of the assembled building to the seismic excitation and the seismic qualification of the structure - was to investigate the behaviour of the column-beam and beam-floor connections. Since the analytical scheme of the column-beam junction simulates the presence of flexural "springs" inserted between these two elements, the tests aimed also at determining the actual stiffness of the joints, and the effects of their possible non-linear behaviour.

To study the overall dynamic response of the frame a vibrodyne was placed on the roof, successively in the two principal horizontal directions, and the vibrations of the structure were recorded by twenty accelerometers. The analysis of the response curves (some of which are shown in fig. 4) allowed six vibration modes to be determined, whose frequencies, damping and shapes are illustrated in fig. 5. As is evident, flexural and flexural-torsional modes were detected. The presence of a torsional component in the response shows that, since the structure is symmetric with respect to the excitation directions, some structural asymmetry arose owing to the behaviour of the joints.

The non-linear effects were investigated by repeating the vibration tests at increasing force levels: as an example, some results of these tests - which refer to the first vibration mode - are illustrated (in terms of transfer functions between response accelerations and exciting force) in fig. 6. The rather large variations of the modal parameters (decrease of the first natural frequency and relevant amplification factor, increase of damping) have to be attributed - besides to the normal variations of the constitutive laws of the materials - mainly to the changes in the behaviour of joints.

In order to investigate in more detail this aspect, some of the joints were carefully monitored with displacement meters, clinometers and strain gauges, installed as schematically shown in fig. 7. These instruments made it possible to highlight two main aspects:

- the behaviour of the same type of joints was not completely similar, owing to mounting and grouting differences. This may account for non symmetric response of the structure, as was inferred from the analysis of the modal shapes;

- the measurement of the displacement and the rotations between the jointed elements (as a function of both the exciting frequency and force intensity), as also the bending moments transmitted to the connection from the column and beam elements, allowed the analytical schematization of the joint (i.e. of the stiffness of the idealized flexural springs) to be calibrated on the basis of the experimental results. This will enable the designer to extend with greater confidence the analytical results to assemblies of a larger number of frames.

It has to be underlined that, as in the case of the box structure described in the previous paragraph, the framed structure withstood for extended periods of time response accelerations higher than those considered by the Italian regulation for first category seismic areas, with damage neither in the reinforced concrete members, nor in the connections.

CONCLUSIONS

Experimental analysis is an indispensable tool for investigating the behaviour of prefabricated structures. Tests on assemblies are preferable to tests on single elements, since they allow a straightforward determination of the dynamic response of the whole structure, and can provide more comprehensive and reliable indications as to be behaviour of the critical parts under the actual loadings transmitted by the vibrating structure.

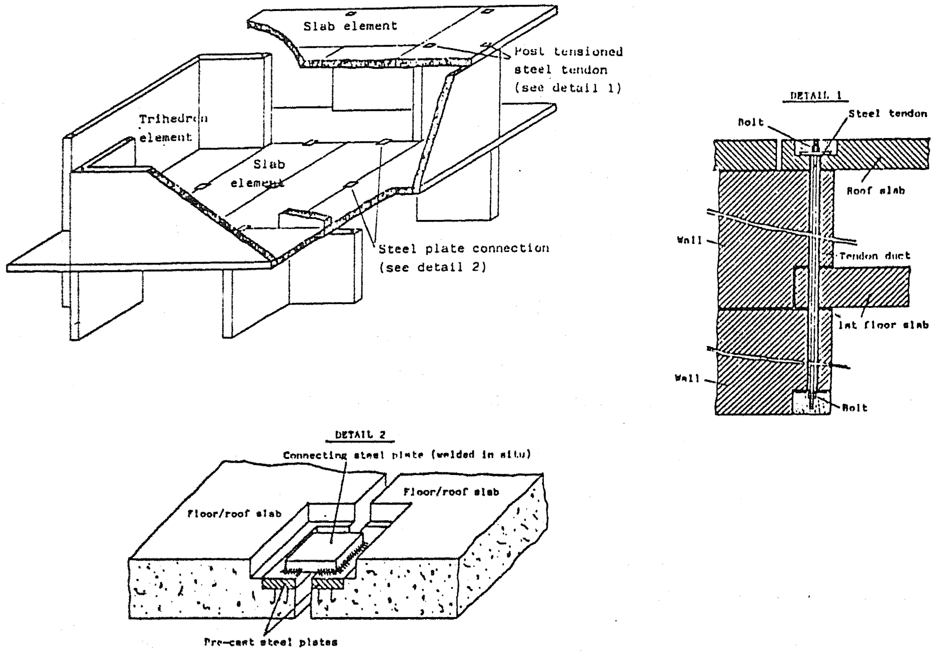

Fig. 1: Schematic representation of the box structure tested.

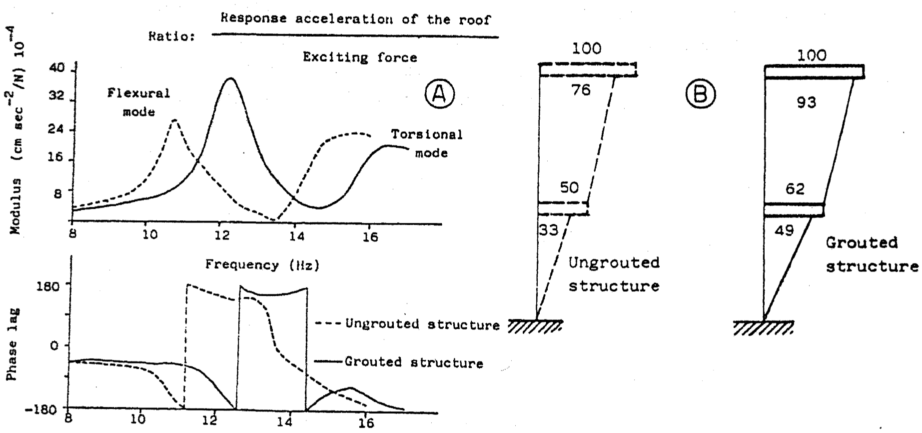

Fig. 2: Box structure: A) Comparison of response curves.
B) Comparison of relative displacements between walls and slabs.

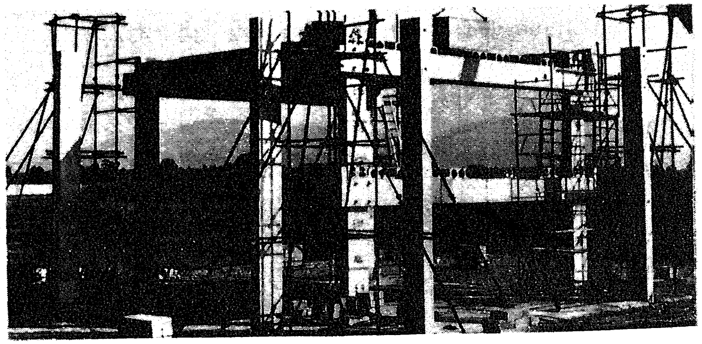

Fig. 3: Framed structure with bolted joints.

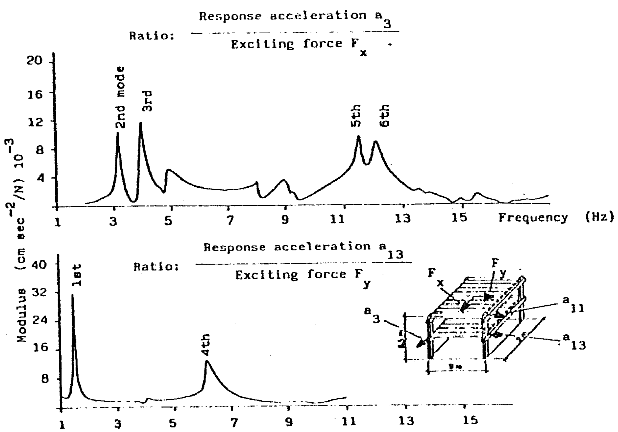

Fig. 4: Framed structure: examples of response curves.

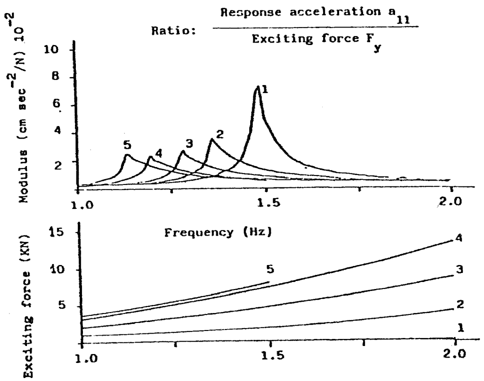

Fig. 6: Framed structure: response variations at increasing forces.

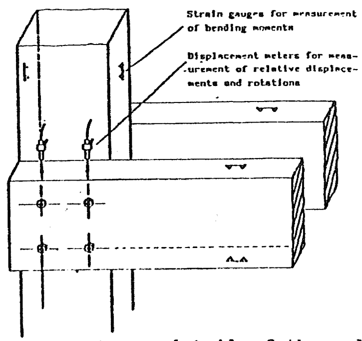

Fig. 7: Framed structure: detail of the column-beam joint with measuring instruments.

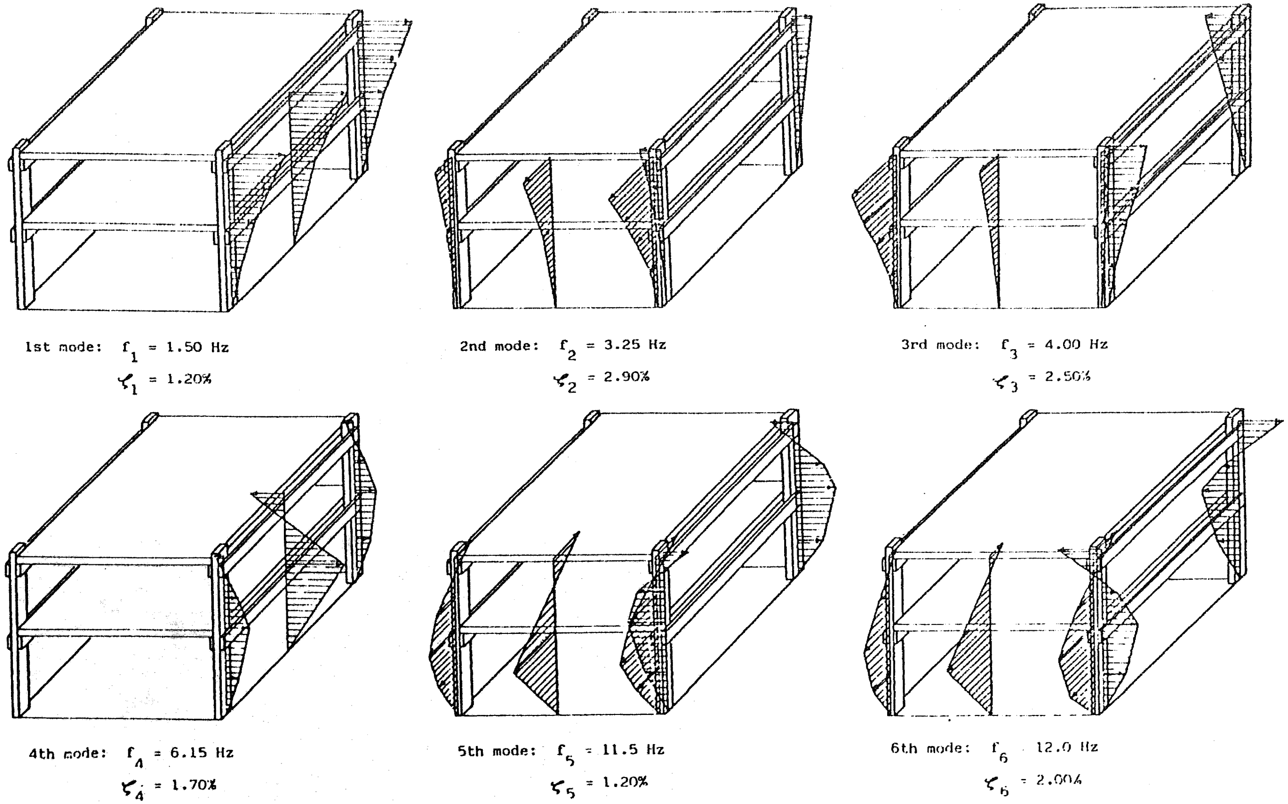

Fig. 5: Framed structure: schematic representation of the first vibration modes.