Full-Scale Shaking Table Tests of XLam Panel Systems - Correlation With Cyclic Quasi-Static Tests

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SUMMARY:
Cross laminated (CLT or XLam) panels are nowadays becoming increasingly popular in seismic prone regions. In order to investigate the dynamic behavior of XLam panel systems under seismic loads, full-scale shaking table tests on two specimens were performed in the laboratory of the Institute of Earthquake Engineering and Engineering Seismology, Skopje. One of the goals of this investigation was to establish correlation with the cyclic quasi-static tests on timber panels with the same geometry, material and anchors that had previously been conducted at the University of Ljubljana. In the paper, the correlation between both types of tests is discussed in terms of force-displacement diagrams. Damping and mass effects appearing during the shaking table tests, which were not present in the quasi-static tests, were the main source of differences between both tests. The paper also comparatively discusses the limitations and the applicability of both test types in seismic evaluation.

Keywords: Xlam, nonlinear FEM analysis, shaking table, force-displacement diagram, cyclic quasi-static test

1. INTRODUCTION

In the paper, full-scale shaking table tests on the first KLH specimen made of massive wooden cross-laminated single-unit panel system which were performed in the laboratory of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje (see Hristovski et al. 2012) are discussed from the point of view of establishing correlation with the cyclic quasi-static tests on timber panels with the same geometry, material and anchors that had previously been carried out at the University of Ljubljana (see Dujic et al. 2004 and 2005). The correlation between the results obtained from both types of tests has been established in terms of force-displacement diagrams. The paper also contains a discussion on the limitations and the applicability of both used test types for the purpose of seismic evaluation of XLam panel systems.

Generally speaking, damping and mass effects appearing during shaking table tests (which are not present in quasi-static tests) are the main source of differences between both tests. Quasi-static tests provide information about the capacity and ductility of XLam panels under “quasi-static” conditions via directly obtained force-displacement diagrams and, on the other hand, shaking-table tests provide information about the real behavior of XLam panels subjected to seismic and harmonic excitations taking into account the dynamic effects. However, the limitation of the shaking-table tests is that it is not always possible to simulate stress-deformation conditions near to failure that can be achieved by use of quasi-static tests. Hence, both tests are complementary and should be performed in order to investigate the seismic behavior of XLam panels.

The correlation between two tests is also affected by differently applied cyclic program. Quasi-static tests are normally performed by using displacement-control schemes with regularly defined cycles; however, on the other hand, the shaking-table tests are conducted using randomly distributed cyclic schemes, depending on the applied ground acceleration input record. Since the non-linear response of any system depends on the history of deformations, it is not possible to establish unique and absolute correlation between both tests in terms of obtained force-displacement hysteretic diagrams. In the paper, one of the discussed correlation aspects was the stiffness in the obtained hysteresis, using the obtained cyclic and envelope quasi-static curve.

A problem arising during the establishment of the correlation between the two discussed tests is that shaking table tests do not explicitly provide force-displacement diagrams, so that they have to be indirectly (semi-analytically) derived. One approach is to use the basic dynamic equation of motion, where the vector of forces appears as a function of absolute acceleration and relative velocity vectors. Since the velocities are not measured directly, they can be estimated using displacements measured by linear potentiometers (LPs). Thus, the velocities, as the first derivatives of displacements, can be approximated using the finite differences method. This is a semi-analytical approach, since it uses both test and analysis. Other approach for construction of the force-displacement diagrams, which has been adopted in this research, is to use finite element analysis (FEA). Since the time-histories of acceleration and displacement obtained by dynamic FEA have corresponded well with the experiments (see Hristovski et al. 2012), the obtained time-histories of the reactions from these analyses have been directly used for construction of the force-displacement diagrams.

The correlation obtained from the performed investigations along with the creation of an optimal combination of experimental and analytical methods led to the development of an optimal methodology for seismic attesting or seismic evaluation of existing or newly designed XLam wooden panel systems. This methodology embraces the basic test of anchors and timber material, ambient-vibration tests, cyclic quasi-static tests and nonlinear FE based numerical modeling. Using this methodology in the design process, the real behavior of the wooden panel systems under seismic actions can be simulated.

2. SHAKING-TABLE AND QUASI-STATIC TESTS

Detailed description of the conducted shaking-table test, including the specimens and instrumentation details is provided in Hristovski et al. (2012). Here, only essential information necessary for understanding the presented material is given. Shaking-table tests have been conducted on the displacement-control IZIIS 5.0x5.0 m shaking-table with bearing capacity of 720 kN and maximum possible displacement of ±0.125 m. The discussed tested specimen KLH 1 consisted of two single-unit panel elements (244/272/9.4 cm) placed in the direction of the applied loading and two secondary panels (190.5/272/9.4 cm) placed in lateral direction. Also, a roof panel (244/210/16.2 cm) was installed on which additional mass of 9.6 t has been applied (see Fig. 1). Instrumentation consisted of 16 linear variable differential transformers (LVDT) for measurement of relative displacements, 2 linear potentiometers (LP) for measurement of absolute displacements and 9 accelerometers (AM) for measurement of accelerations.

Figure 1. Specimen KLH 1 mounted on shaking-table

Tests which are discussed in the paper are given in Table 1. The complete test protocol can be found in

Hristovski et al. (2012). Note that the ambient-vibration tests were conducted prior to the shaking-table tests for the purpose of definition of the initial natural periods of vibrations of the tested specimen. Also, after each series of tests, a random vibration test has been applied in order to check if some change in the first period of vibration has occurred, which can indicate stiffness deterioration i.e., damage to the specimen. However, no significant change of the natural period of vibration has occurred during the complete test protocol.

Table 1. A part of the test protocol for KLH specimen 1 and applied maximum peak acceleration (given in g=9.81 m/sec^2)

Test	$a_{g,max}$
Test 03 - El Centro, horiz. comp. span* 100	0.032g
Test 05 - Kobe JMA NS horiz. comp. span 100	0.040g
Test 06 - Tolmezzo, horiz. comp. span 100	0.107g
Test 07 - Albstadt, horiz. x-comp. span 65	0.216g
Test 14 - Tolmezzo, horiz. y-comp. span 300	0.295g
Test 16 - El Centro, horiz. comp. span 850	0.291g
Test 25 - Kobe, JMA EW comp. span 700	0.301g
Test 27 - Petrovac, horiz. comp. span 550	0.370g
Test 29 - Harmonic (sine) test 7.5Hz, span 10	0.153g
Test 30 - Harmonic (sine) test 7.5Hz, span 15	0.235g
Test 31 - Harmonic (sine) test 7.5Hz, span 20	0.322g
Test 32 - Harmonic (sine) test 7.5Hz, span 25	0.405g
Test 33 - Harmonic (sine) test 7.5Hz, span 30	0.499g
Test 35 - Harmonic (sine) test 7.5Hz, span 35	0.608g
Test 36 - Harmonic (sine) test 7.5Hz, span 40	0.697g
Test 37 - Harmonic (sine) test 7.5Hz, span 45	0.792g

* 1 span = 1/1000 of max horizontal displacement of the shaking table

Fourier spectra for the simulated El Centro (span 850) and Kobe JMA EW (span 700) earthquakes excitations are given in Figs. 2a and 2b, respectively.

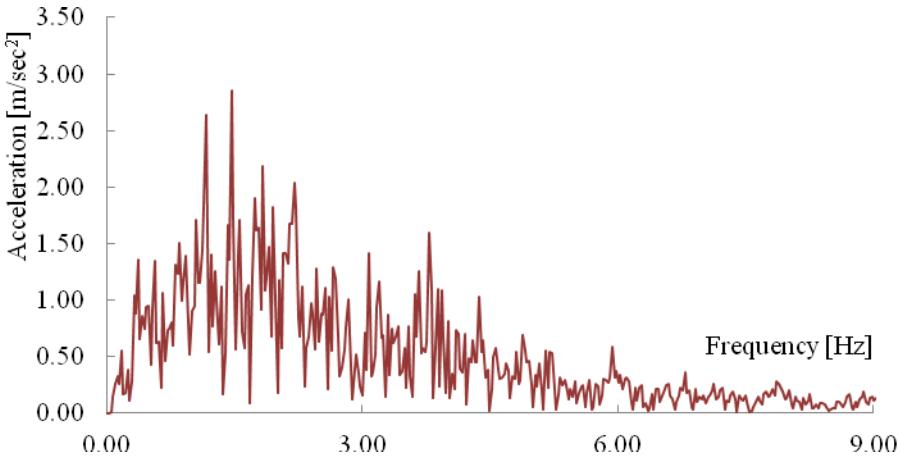

Figure 2a. Fourier spectrum of El Centro (span 850) input acceleration, test 16

As to the cyclic quasi-static tests previously conducted at the University of Ljubljana, detailed description can be found in Dujic et al. (2004) and (2005). In total, 53 panel specimens have been tested subjected to monotonic and/or cyclic quasi-static excitations, using 14 general types of single-unit and two-unit setups under variable conditions related to the applied anchorage system, length of nails, specimen dimensions, applied axial load, existence of openings (fenestrated and solid specimens), applied boundary conditions, etc. The tested specimens from this series of quasi-static tests denoted as W6c/1 (for two-unit panels) and W7c/2 (for single-unit panels) correspond to the shaking-table tested KLH specimen 2 and KLH specimen 1, respectively. In this paper, only the results obtained for the shaking-table unit-panel specimen (KLH specimen 1), i.e., quasi-static tested specimen W7c/2 will be comparatively discussed. The obtained maximum force for specimen W7c/2 was 65.05 kN and the corresponding displacement was 40.32 mm. The force-displacement envelope diagram for this specimen obtained from the cyclic quasi-static test is shown in Fig. 3.

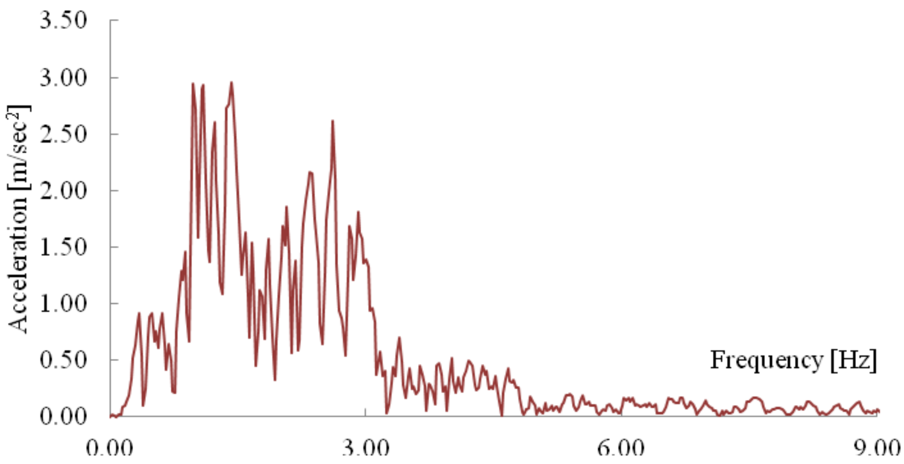

Figure 2b. Fourier spectrum of Kobe JMA-EW (span 700) input acceleration, test 25

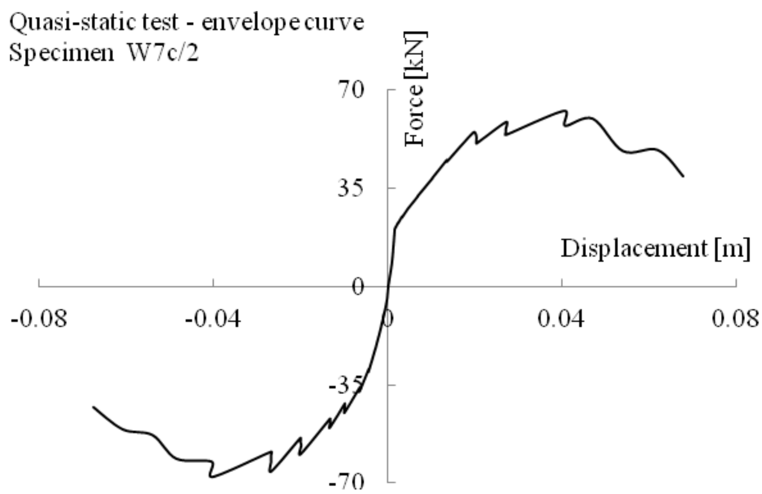

Figure 3. Envelope force-displacement diagram obtained from the cyclic quasi-static test for specimen W7c/2

3. FINITE ELEMENT ANALYSES AND CONSTRUCTION OF HYSTERETIC LOOPS

In Hristovski et al. (2012), the implemented finite element based analytical model and non-linear constitutive relationships for the anchors and the contact zone between the panel and the foundations have been discussed in details and the obtained time-histories of the displacements and accelerations have been presented. Herein, only the results regarding the force-displacement hysteretic loops obtained by the finite element analyses are given and compared with the force-displacement diagrams obtained from the quasi-static cyclic tests. The finite element time-history dynamic analyses have been performed by use of the FELISA/3M software package, original product of IZIIS, Skopje. The finite element model consisted of 2D orthotropic continuum representing the cross-laminated timber panel discretized with iso-parametric plane elements and link elements for modelling the connections (the anchors and the contact zone between the panel and the foundation), as shown in Fig. 4.

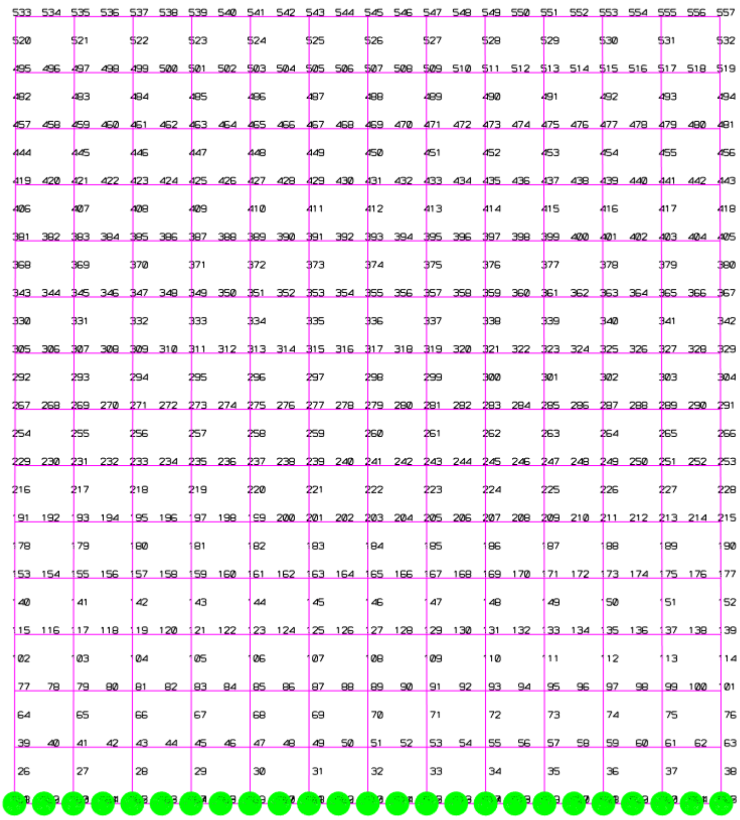

Figure 4. Finite element model (green areas represent link elements)

The construction of the horizontal force-displacement diagram has been performed automatically in the analyses as a summation procedure of the horizontal reactions in the supporting nodes and in the nodes where the mass has been applied. Some of the obtained hysteretic diagrams are presented in Figures 5 (presented as brown dotted diagrams). For the purpose of comparison, a part of the quasi-static force-displacement envelope diagram is also shown in all figures (presented by a black solid line).

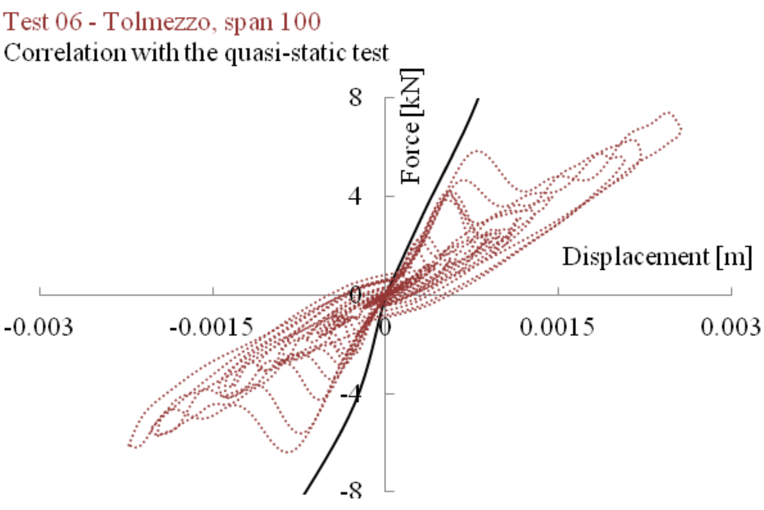

Figure 5.1 Obtained hysteretic force-displacement diagrams and correlation with the quasi-static test envelope for Test 06

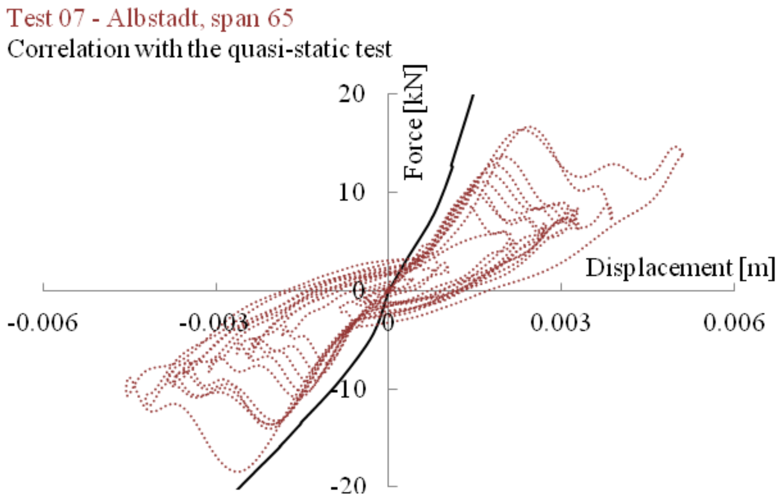

Figure 5.2 Obtained hysteretic force-displacement diagrams and correlation with the quasi-static test envelope for Test 07

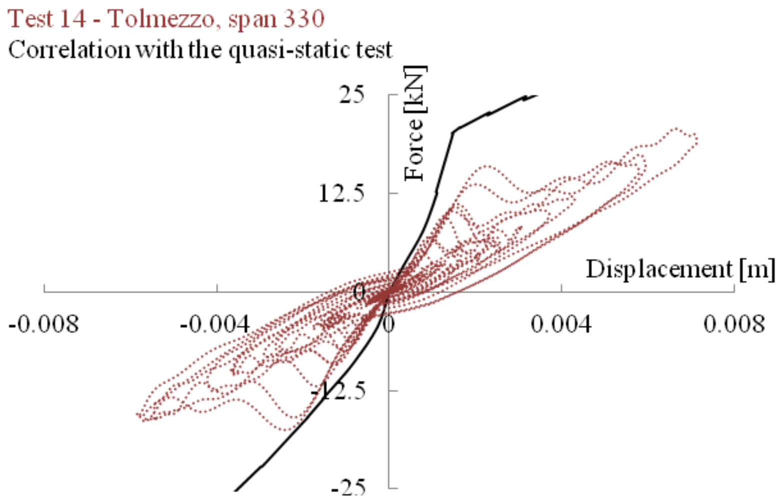

Figure 5.3 Obtained hysteretic force-displacement diagrams and correlation with the quasi-static test envelope for Test 14

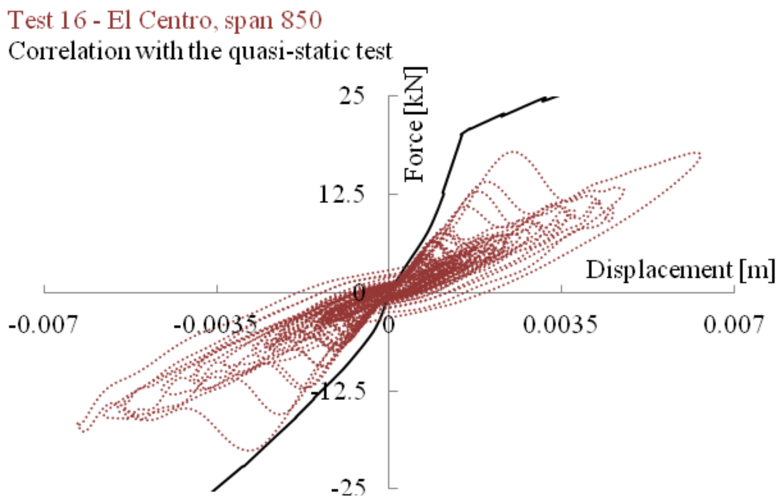

Figure 5.4 Obtained hysteretic force-displacement diagrams and correlation with the quasi-static test envelope for Test 16

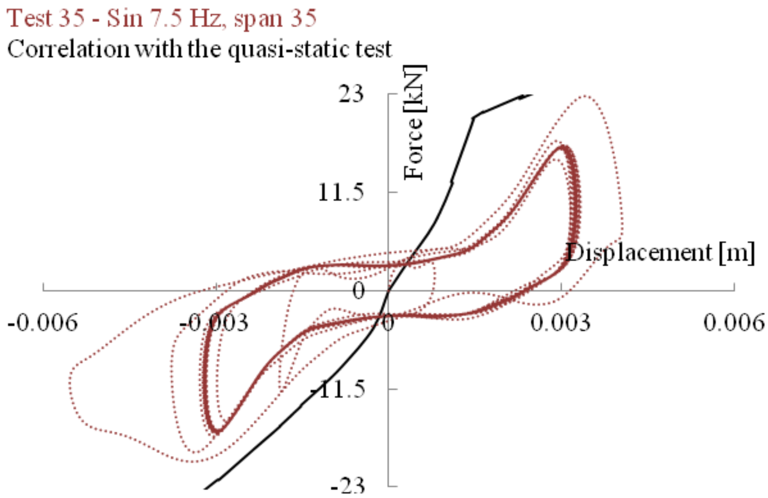

Figure 5.5 Obtained hysteretic force-displacement diagrams and correlation with the quasi-static test envelope for Test 35

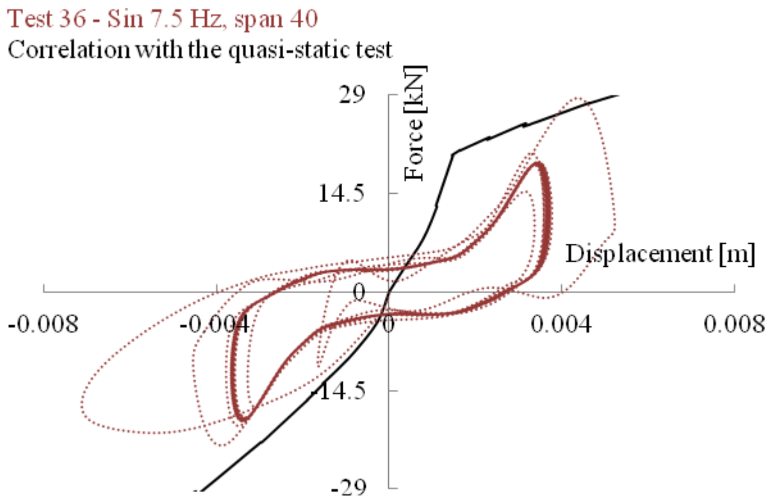

Figure 5.6 Obtained hysteretic force-displacement diagrams and correlation with the quasi-static test envelope for Test 36

The correlation of the dynamic hysteretic curves and the cyclic quasi-static hysteretic curve is given in Figure 6.

4. METHODOLOGY FOR SEISMIC EVALUATION OF XLAM PANEL SYSTEMS

The results from the performed investigation led to development of a methodology for seismic evaluation of XLam panel systems, herein presented briefly. It is obvious that shaking table tests are quite expensive and their implementation will probably be reduced to seismic tests of new products, that is, new systems made of this material. On the other hand, an optimal combination of experimental and analytical methods will produce a powerful and relatively cheap procedure for seismic evaluation of existing XLam wooden panel systems. This approach embraces the following steps:

Step 1 - First, basic quasi-static tests of the anchors need to be performed in order to obtain the required nonlinear constitutive force-displacement relationships in normal and tangential direction. Conducting of the basic tests is also needed for definition of the basic mechanical properties of the XLam wooden panel material such as Young’s modulus of elasticity in the two directions of the panel’s plane, the shear modulus as well as the Poisson’s ratio.

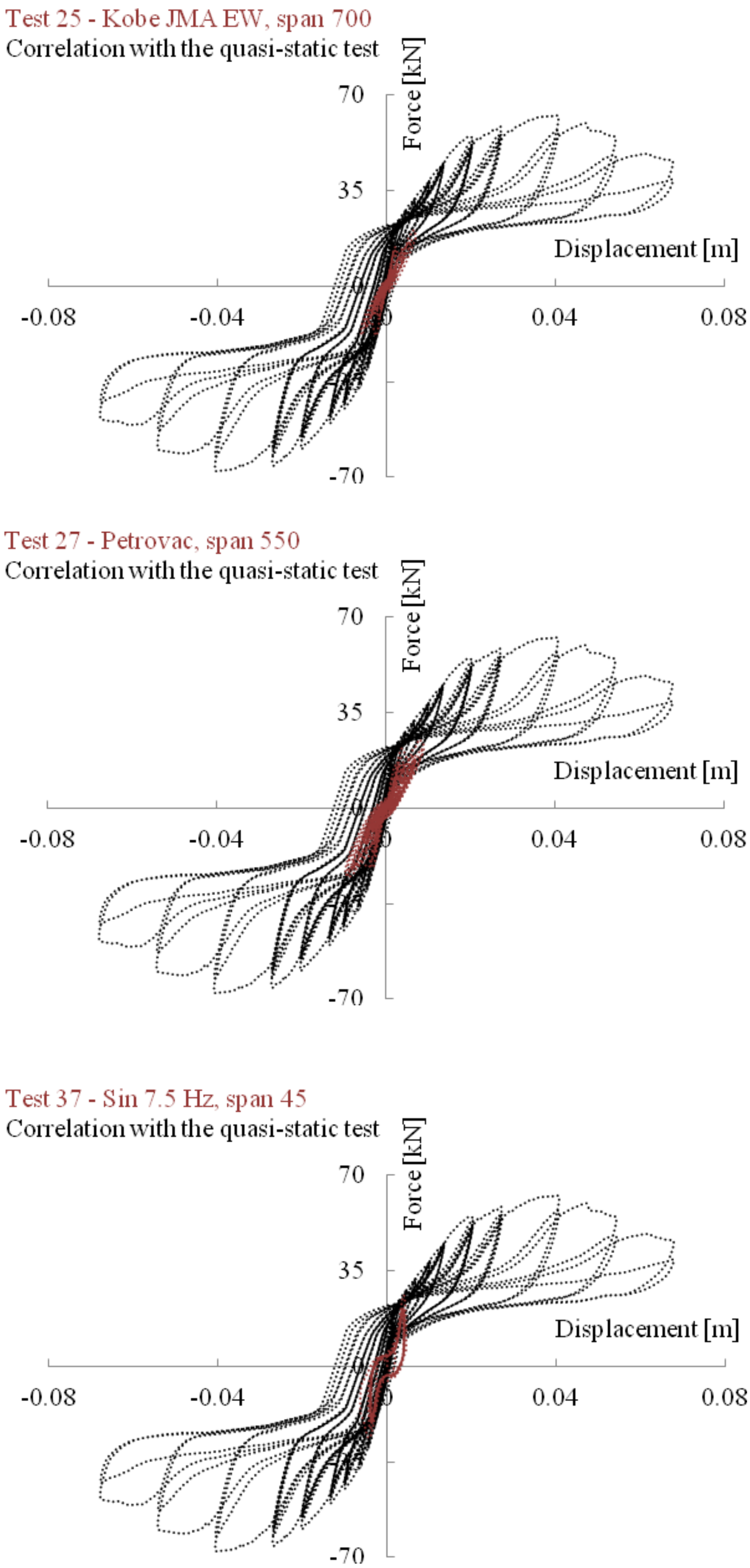

Figure 6. Correlation of the quasi-static and dynamic hysteretic curves

Step 2 - Then, information about the capacity and ductility of the panel elements in terms of hysteretic force-displacement diagrams can be obtained using quasi-static cyclic tests.

Step 3 - Once the structure is assembled, ambient vibration tests are carried out in order to define the real periods of vibration of the systems in horizontal directions.

Step 4 - Then, an analytical model is created and the initial stiffness of the system is identified taking into consideration the results from the ambient vibration tests.

Step 5 - Approximation of the constitutive relationships for the connections obtained in step 1 is done. Also, the results from step 3 are used for definition of the constitutive relationships at the contact zones in tangential and normal direction.

Step 6 - Finally, the finite element model is defined with the incorporated nonlinear constitutive relationships for the connections and the contact zone, using an appropriate computer program (i.e. the FELISA/3M software package), and then dynamic analyses with given real and/or synthetic ground acceleration records are run. The input, in terms of static forces, spectrum or ground acceleration records can be adjusted according to the Eurocode 8 for timber structures.

Following the above-explained methodology, the real behavior of the wooden panel systems under seismic actions can be simulated during the seismic evaluation and design process.

5. CONCLUSION

Experimental and analytical investigations on XLam wooden panels, KLH type with BMF anchor system have been carried out in order to define their behavior when subjected to seismic actions. In the experimental part of this investigation, shaking table dynamic tests on two 3D full scale models made of XLam wooden panels have been performed. The tested models were subjected to real and sinusoidal input ground acceleration time histories as well as ambient and forced vibration test required for determination of the models' natural periods and frequencies. The analytical part of the investigations has included definition of the physical model of the systems, determination of the constitutive nonlinear relationships for the anchor system and the contact zone between the panels and the reinforced concrete foundations as well as definition of the numerical models using the finite element method and thus obtaining the response time histories of the systems from the given input ground acceleration time histories simulated during the shaking table tests.

Generally, the shaking-table tests have proved the ductile behavior of the connections and exhibited good correlation with the results from the quasi-static tests. Especially, the obtained hysteretic diagrams from the presented dynamic analyses have shown good correlation with the quasi-static force-displacement diagrams. The shaking-table tests (with maximum applied peak acceleration of 0.37g) mobilized only about $1/3^{rd}$ of the capacity of the XLam systems obtained from the quasi-static test. This has confirmed the good behavior of this system under seismic excitations. On the other hand, the research emphasized the necessity of quasi-static tests because they can provide information on near to failure structural states that is not possible with the shaking-table tests. Therefore, both shaking-table and cyclic quasi-static tests are necessary in order to investigate the behavior of XLam systems. However, the methodology explained in Chapter 4 in combination with Eurocode 8 might be sufficient for practical design.

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REFERENCES

Hristovski, V., Dujic, B., Stojmanovska, M. and Mircevska, V. (2012). "Full-Scale Shaking-Table Tests of XLam Panel Systems and Numerical Verification – Part 1: Specimen 1." Submitted manuscript # STENG-1775 to the *ASCE Journal of Structural Engineering*, (under review)

Dujic, B., Pucelj, J. and Zarnic, R. (2004). "Testing of Racking Behaviour of Massive Wooden Wall Panels." *Proc. of CIB*, Edinburgh, Scotland, W18/37-15-2.

Dujic, B., Aicher, S. and Zarnic, R. (2005). "Investigation on In-plane Loaded Wooden Elements – Influence of Loading and Boundary Conditions." *Otto Graf Journal*, *Materialprüfungsanstalt Universität Stuttgart, Otto-Graf-Institut (FMPA), MPA Stuttgart*; Vol.16 2005.