Shaking Table Test of Innovative Composite Panel Composed of Glued Laminated Wood and Bearing Glass

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SUMMARY:
The paper shows the results obtained by seismic testing of innovative composite panels, i.e. a model composed of glued laminated wood and bearing glass tested on the shaking table in the Institute of Earthquake Engineering and Engineering Seismology - UKIM IZIIS, Ss. Cyril and Methodius University, Skopje, Macedonia. The investigation has been performed within the frames of the bilateral scientific project between UKIM-IZIIS and the Civil Engineering Faculty, University of Zagreb, Croatia. The results will be used for development of a mathematical model appropriate for design of such structural elements and analyses of the interaction between them and the surrounding structure. Particular attention has been paid to the valuable information and measured response parameters referring to dissipation of energy at the connections between the glass and the wooden structure.

Keywords: Shaking table, composite panel, glued laminated wood, bearing glass, seismic stability

1. INTRODUCTION

In modern architecture and building construction, glass panels are not used only as facade elements, but also as a part of the main structure. The glass is a material with very high compressive strength and modulus of elasticity, which is around 1/3 of the modulus of elasticity for steel. But, as a material, the glass is not ductile but brittle and behaves elastically until failure. For these reasons, in the case when glass is used for the main carrying elements, a special detailing and design of the contacts between all the elements of the structural system should be carried out.

Considering the review of investigations of glass panels that have been done in Europe, it can be concluded that the researchers have paid attention neither to the connections composed of timber frames and glass panels nor to the seismic loading of such elements.

The main purpose of the bilateral scientific project between the Institute of Earthquake Engineering and Engineering Seismology - UKIM-IZIIS, St. Cyril and Methodius University, Skopje, Republic of Macedonia and the Civil Engineering Faculty, University of Zagreb, Croatia, entitled "Seismic Resistance of Timber-Structural Glass Systems with Optimal Energy Dissipation" was to develop a simple diaphragm configuration of a glued laminated wood and bearing glass and to test the main characteristics under the effect of in-plane loads. Development of a mathematical model to be used in design of such structural elements and analyses of the interaction between them and the surrounding structure was one of the activities, as well. The tested structural element was developed within the research cooperation between the Faculty of Civil and Geodetic Engineering of University of Ljubljana, Slovenia and the Civil Engineering Faculty, University of Zagreb, Croatia before launching of the above mentioned bilateral cooperation.

Within the project, experimental testing of full scale composite timber-glass innovative panels was carried out on the seismic shaking table at IZIIS for the purpose of defining their behaviour and stability under real earthquake conditions.

2. DESCRIPTION OF THE TESTED MODEL

The model was composed of two identical innovative panels. Each panel consisted of a pair of two 10 mm sheets of toughened glass laminated together and framed by a glued laminated wooden frame. The panel was 320 cm long and 272 cm high. The cross-section dimensions of the posts and the girts were equal, 9.2 cm in width and 16 cm in height. The posts and girts were connected in each corner by a steel bolt having a diameter of 24 mm fixed over the punched metal plates (Figure 9). In lateral direction, a solid glued laminated wooden panel having dimensions of 190/270/9 cm was placed for preventing the out-of-plane deformation of the main panels. Four ribbed corner connectors 105/105 mm were used to fix each panel to the reinforced concrete foundation beam by two bolts M12. Each corner connector was fixed to the wooden frame by 10 4/60 mm annular nails.

When planning the experimental seismic testing of the model composed of the innovative panels, the idea was to consider a real 3-storey structure. In that respect, additional mass of 10.6t was placed and connected rigidly to the wooden roof slab. This applied load was in correspondence with the gravity load applied to the previously tested panels (in-plane) in quasi-static conditions in the Laboratory of the Faculty of Civil and Geodetic Engineering of the University of Ljubljana. In such way, the comparison between the obtained results on that occasion with the results obtained during the seismic tests presented herein, was possible.

Some photos showing the innovative panels, the assembled model as well as the loaded and the instrumented model ready for seismic testing on the shaking table are given in Figures 1 and 2.

Figure 1. Model assembling - fixing of the two composite panels (left), completed model (right)

Figure 2. Loaded and instrumented model ready for testing

3. TEST SET-UP

3.1. IZIIS Shaking Table

The model was assembled and tested on the seismic shaking table at the IZIIS Laboratory. This shaking table represents a pre-stressed reinforced concrete plate with dimensions 5x5 m in plan and has the possibilities for simulation of different types of dynamic motion: random, harmonic, impulse, earthquake etc. Four vertical hydraulic actuators support it. The working frequency range of the shaking table is 0.1-80Hz, and the maximum mass of a model is limited to 40t.

The max accelerations are 0.7g in horizontal and 0.5g in vertical direction, and the max. displacements are 0.125m in horizontal and 0.05m in vertical direction. The shaking system controls five degrees of freedom of the table, two translations and three rotations. This three-variable control system (MTS) is capable to control displacements, velocities and accelerations, simultaneously.
For earthquake generation and data acquisition, a modular PXI system is used.

3.2. Instrumentation of the Model

For the seismic tests, the model was instrumented for measuring the input as well as the response at characteristic points. Both panels had the same instrumentation - 10 LVDT's and 7 SG. At the top of the model, there were 4 accelerometers, one at each corner. 2 LP's were placed at the level of the foundations and 2 at the top to measure the absolute displacement of the model. Considering that the connection between the glass and the wooden frame is of crucial importance for the stability of the panel during the seismic action, as well as the location where the energy is dissipated during the strong shaking, several LVDT's for measuring the slippages and deformation were placed at the critical points. To obtain information about the strains in the glass panels, 14 strain gages were used. The total number of channels was 44, as presented in Figures 3 and 4 and in Table 1.

The real time recording of the model response was performed by a 72-channel high-speed data acquisition system.

Table 1. Instrumentation of the model

Description/Position	Instrument	Channel (CH)
Foundation of the model	Acc.	CH1, CH2
Foundation of the model	LP	CH9, CH10
Top of the model	Acc.	CH3,CH4, CH5,CH6
Top of the model-right side	LP	CH11
Top of the model-left side	LP	CH12
Foundation of the model	LVDT	CH13, CH30
Top of the model	LVDT	CH14, CH31
Slip between the foundation and the shaking table	LVDT	CH15, CH32
Uplifting of the panels	LVDT	CH16, CH21, CH33, CH38
Deformation of the wooden frame	LVDT	CH17, CH20, CH34, CH37
Slip between the glass and the wooden frame	LVDT	CH18, CH22, CH35, CH39
Slip between the foundation and the wooden frame	LVDT	CH19, CH36
Strains in the glass	SG	CH23,CH24,CH25,CH26,CH27,CH28,CH29, CH40,CH41,CH42,CH43,CH44,CH45,CH46

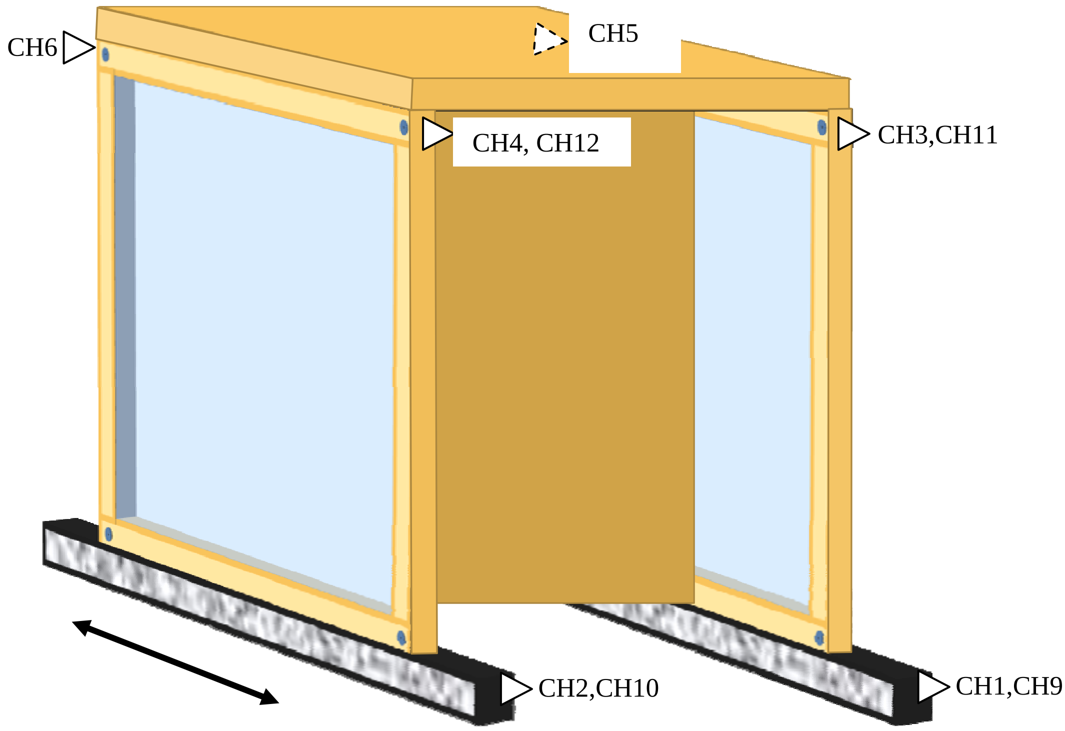

Figure 3. Instrumentation of the model with accelerometers and LP's

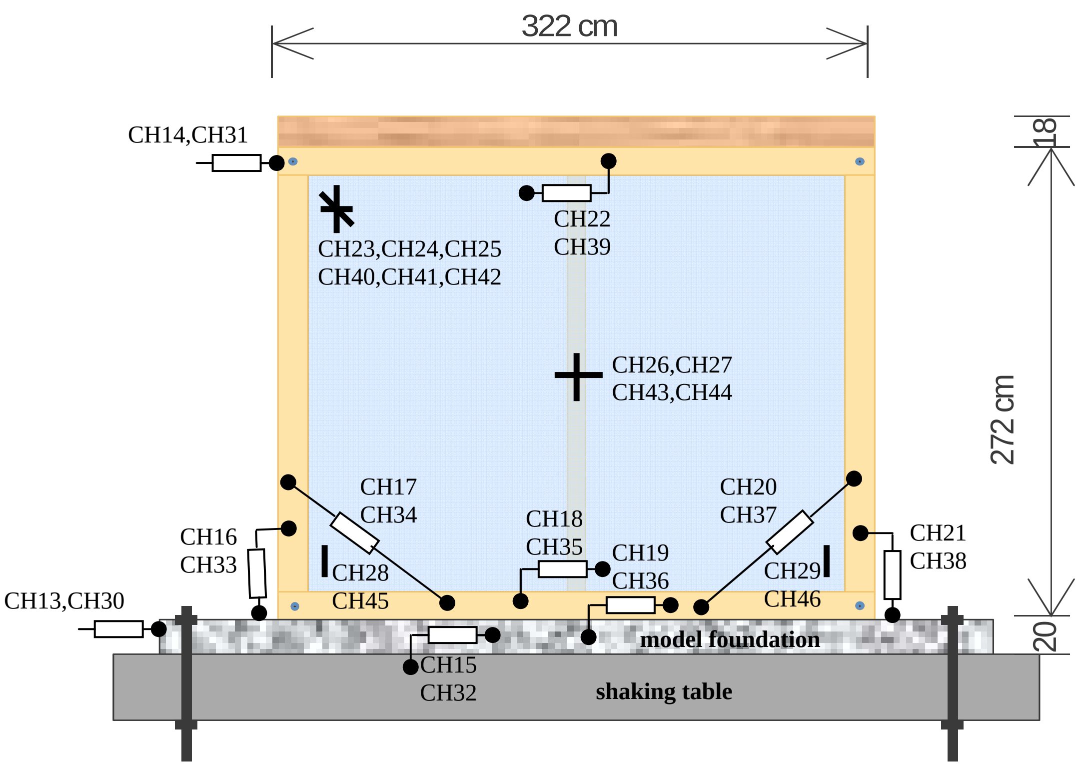

Figure 4. Instrumentation of the model with LVDT's and SG (on the glass)

3.3. Testing Procedure

3.3.1. Dynamic Characteristics of the Model

Before the seismic testing, the dynamic characteristics of the model were obtained by measuring the ambient vibrations at selected points and processing the records by use of the Artemis software. The obtained results are given in Figure 5 and in Table 2.

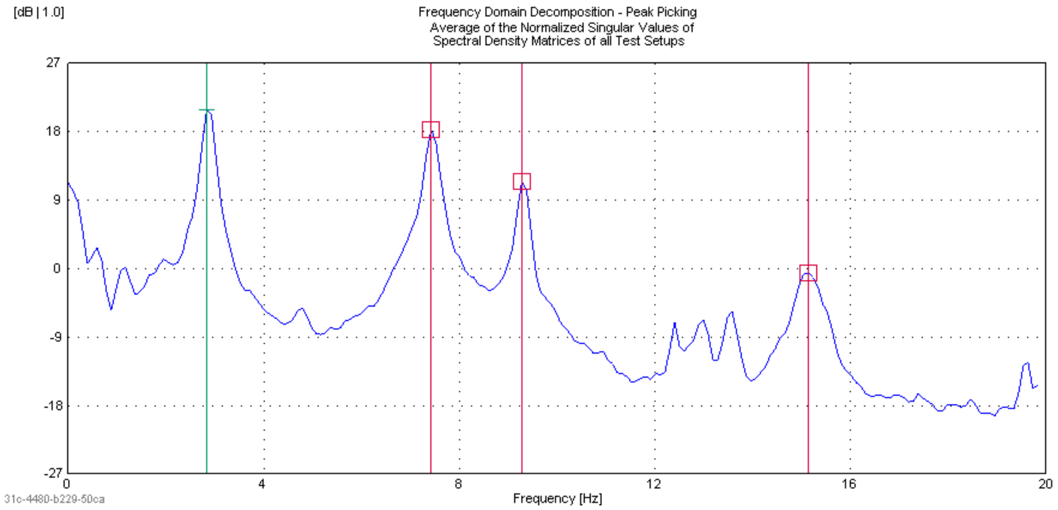

Figure 5. Peak picking of the dominant frequencies

Table 2. Dominant frequencies of the model

Mode	Frequency [Hz]	Direction
FDD Mode 1	2.83	Longitudinal
FDD Mode 2	7.42	Transversal
FDD Mode 3	9.28	Torsion
FDD Mode 4	15.14	

3.3.2. Seismic Shaking Table Tests

The seismic excitations selected for the shake-table testing of the model were four representative accelerograms recorded during the following earthquakes: El Centro (a_{max}=0.34g), Petrovac (a_{max}=0.47g), Kobe (a_{max}=0.58g) and Friuli (a_{max}=0.31g). The idea was to investigate the seismic behavior of the model under several types of earthquakes, considering their different frequency content, peak acceleration and time duration. The tests were performed in series, with increasing intensities until the damage occurrence in the model. The applied input intensities in a series were decided to be around the same percentage of the max. acceleration (full scale) of the applied earthquake. The model frequencies were checked after each series of test by random excitation or by sine-sweep test. The final tests were performed by using the most unfavorable excitation, i.e. the Kobe earthquake because it produced very intensive shaking and response of the model. The last 4 tests were performed by harmonic excitation having frequencies equal to the frequencies of the model after the seismic tests accomplishment, f=4.0Hz and f=6.0 Hz, in order to see the effects of the resonance conditions.

Presented in Table 3 are the performed tests, the input intensity measured at the level of the model foundation, as well as the max. response acceleration measured at the top of the model.

Table 3. Performed tests on the shaking table

Test No.	Excitation	Input acc. (g)	Max. response acceleration (g)	Damage Occurrence
2	Random test 0-15Hz	0.02	-	
3	El Centro earthquake	0.046	0.09	
4	Petrovac Earthquake	0.058	0.07	
5	Kobe Earthquake	0.06	0.08	
6	Friuli Earthquake	0.04	0.06	
7	Random test 0-15Hz	0.02	-	
8	El Centro Earthquake	0.14	0.20	
9	Petrovac Earthquake	0.13	0.16	
10	Kobe Earthquake	0.14	0.20	
11	Friuli Earthquake	0.10	0.19	
12	Random test 0-15Hz	0.02	-	
13	El Centro Earthquake	0.25	0.35	
14	Petrovac Earthquake	0.27	0.35	
15	Kobe Earthquake	0.30	0.45	
16	Friuli Earthquake	0.17	0.38	
17	Random test 0-15Hz	0.02	-	
18	El Centro Earthquake	0.35	0.50	
19	Petrovac Earthquake	0.45	0.50	
20	Kobe Earthquake	0.50	1.0	First damage
21	Friuli Earthquake	0.25	0.5	
22	Friuli Earthquake	0.30	0.5	
23	Random test 0-15Hz	0.02	-	
24	Kobe Earthquake	0.60	0.8	Damage development
25	Random test 0-15Hz	0.02	-	
26	Kobe Earthquake	0.50	1.0	
27	Sine-sweep 0-15Hz	0.06	-	
28	Harmonic test f=4.0Hz	0.04	0.17	
29	Harmonic test f=4.0Hz	0.08	0.36	
30	Harmonic test f=6.0Hz	0.04	0.14	
31	Harmonic test f=6.0Hz	0.08	0.22	

4. EXPERIMENTAL RESULTS

In the first series of seismic tests, the intensity was low, reaching the values of 4-6 %g. The second and the third series were with intensities of 10-14%g and 17-30%g, respectively. The model was vibrating intensively, but in a very stable manner. No damage was noticed. The time histories of input motion (0.3g) and the response of the model for this test under the Kobe earthquake are given in Figure 6.

In the fourth series of tests, when the input intensities reached 35%-50%g, the response acceleration at the top of the model reached twice the input value of the Kobe and Friuli earthquake - 1g and 0,5g, respectively (see Table 3). The vibration was very intensive, especially during the Kobe earthquake with a=0.5g, and the first damages occurred in the upper beam of the wooden frame. Presented in Figure 7 are the time histories of the input acceleration and displacement for the Kobe earthquake as well as the response of the model at the top. The time histories of input acceleration and displacement as well as response of the model during the final test with intensity of 0.6g - Kobe earthquake are presented in Figure 8. During this test damage developed and it was only in the wooden frame. Although the vibration of the model was very strong, there was no damage or cracks in the glass. The whole mechanism of energy dissipation during the shaking developed in the wooden frame, expressed through sliding of the glass in contact with the frame. This was the main idea during the development of the innovative composite panel and in the design of the connection between the glass and the frame. The photo presenting the type of damage in the wood is given in Figure 9.

The slip between the glass and the wooden frame for both panels during the test with intensity 0.5g, as well as during the test with intensity 0.6g is presented in Figures 10 and 11, respectively. The max. slip value reached around 33mm. It is evident that there is a residual deformation in the corner connection of 8 mm.

In the final tests performed with intensive harmonic excitations of 8%g, no additional damage was observed.

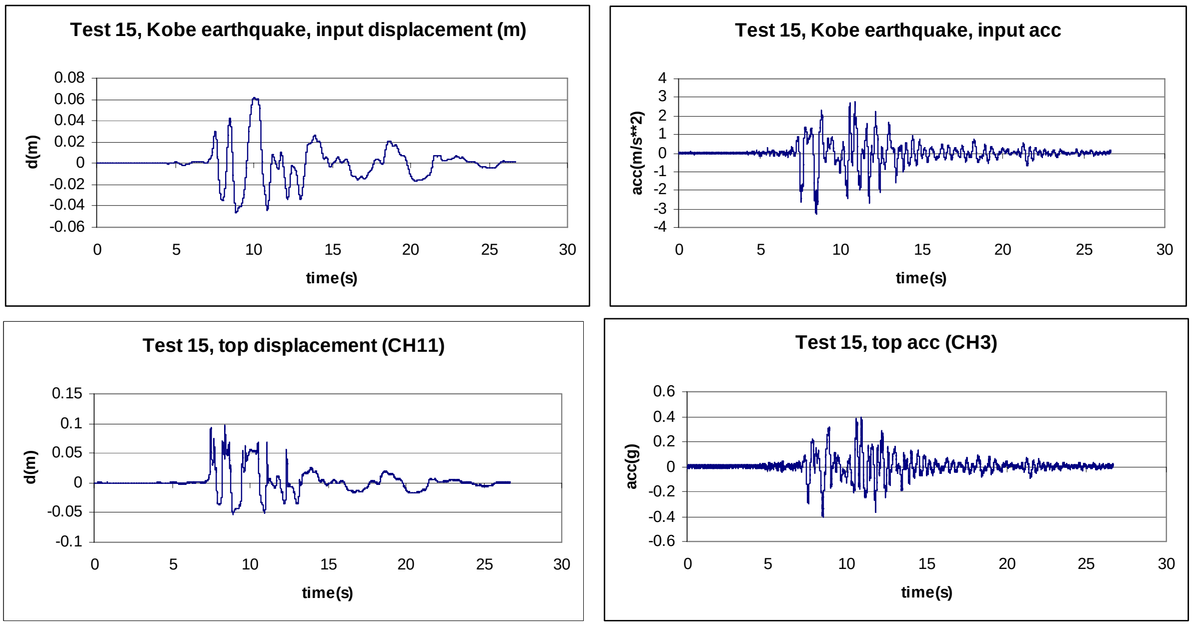

Figure 6. Input motion and response of the model, Kobe earthquake, test 15

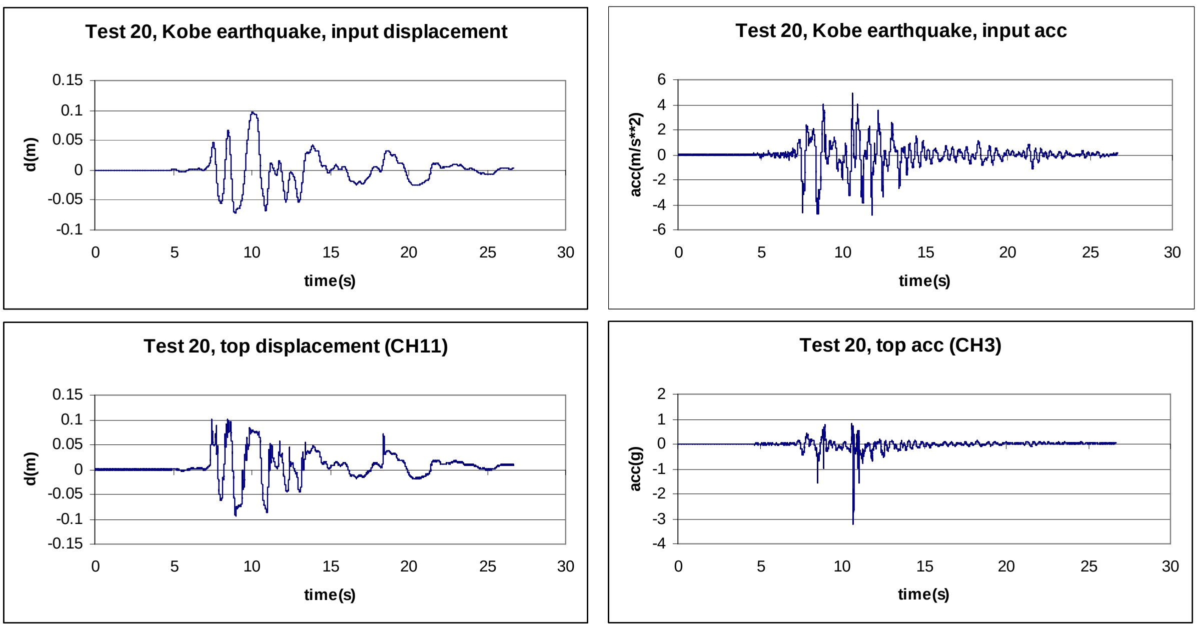

Figure 7. Input motion and response of the model, Kobe earthquake, test 20

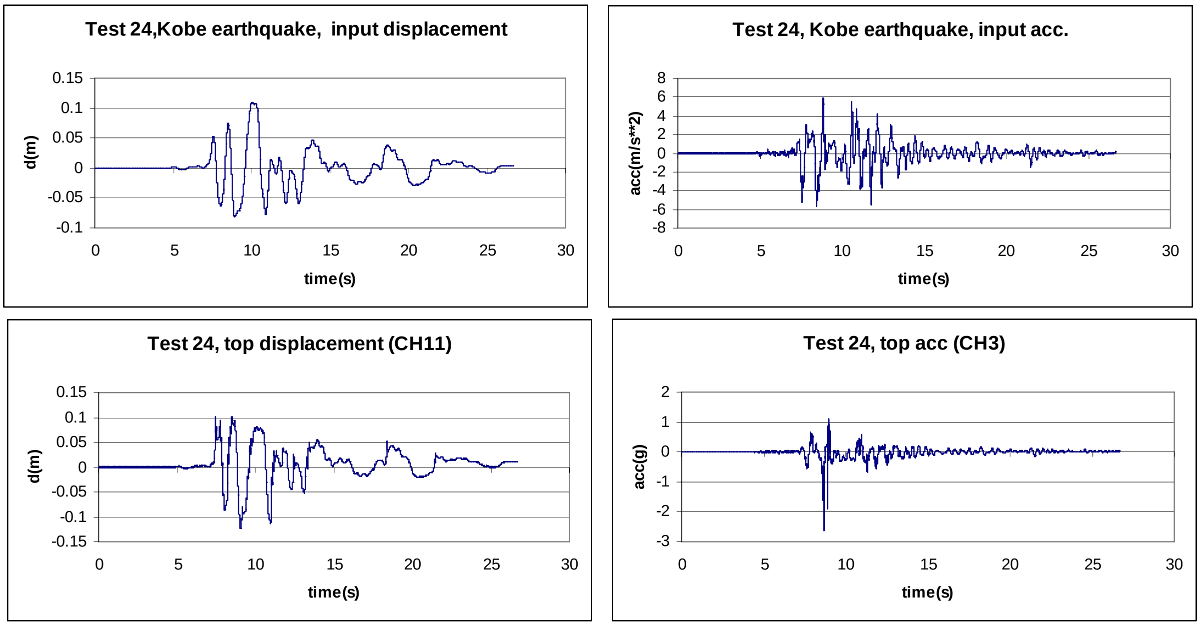

Figure 8. Input motion and response of the model, Kobe earthquake, test 24

Figure 9. Detail of damage in the wooden frame

5. CONCLUSIONS

The seismic shaking table testing of the model composed of innovative panels of glued laminated wood and bearing glass was successfully carried-out on the shaking table in the IZIIS laboratory.

The performed tests showed clearly the behaviour of the composite panels and the failure mechanism under strong earthquake motion. It is manifested by slip of the glass along the wooden frame and permanent deformations in the wood, without any damage in the glass. The panels dissipated energy trough sliding of the glass and activating of the connectors (connection) in the corners of the wooden frame.

The connections in the wooden frame are considered essential part of the panel in the failure mechanism development.

The seismic tests proved that the innovative composite panel can be considered as a promising structural system, in which the bearing glass and the wood are working together, conforming to each other in a beneficial manner.

The dynamic tests results showed very good agreement with the results obtained during the quasi-static tests of the panels.

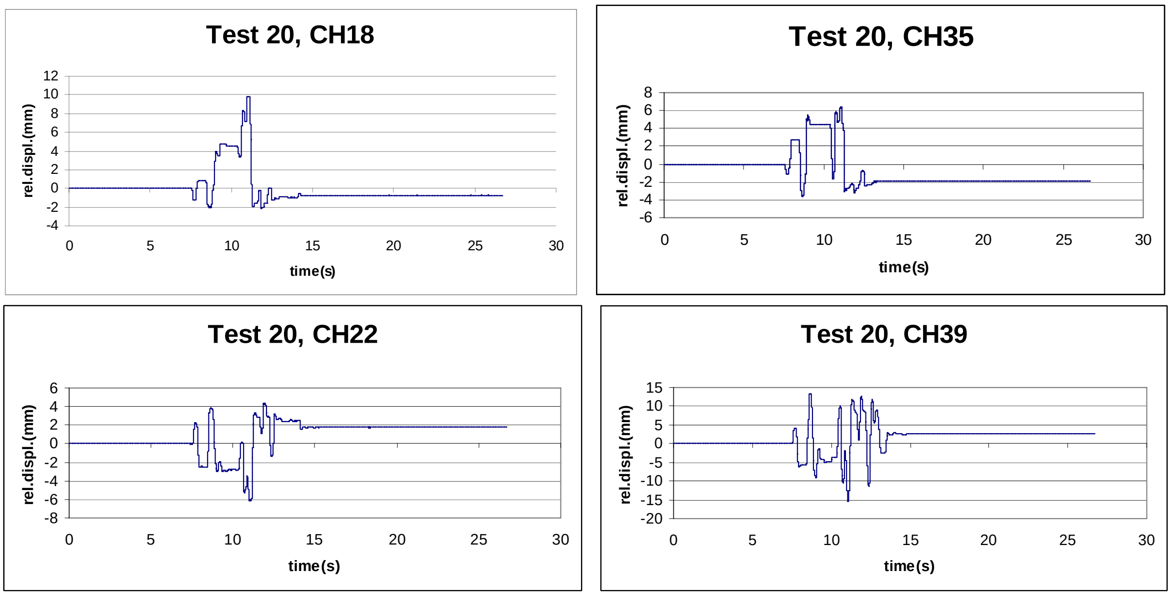

Figure 10. Slipping between the glass and the wooden frame during the Kobe earthquake, test 20

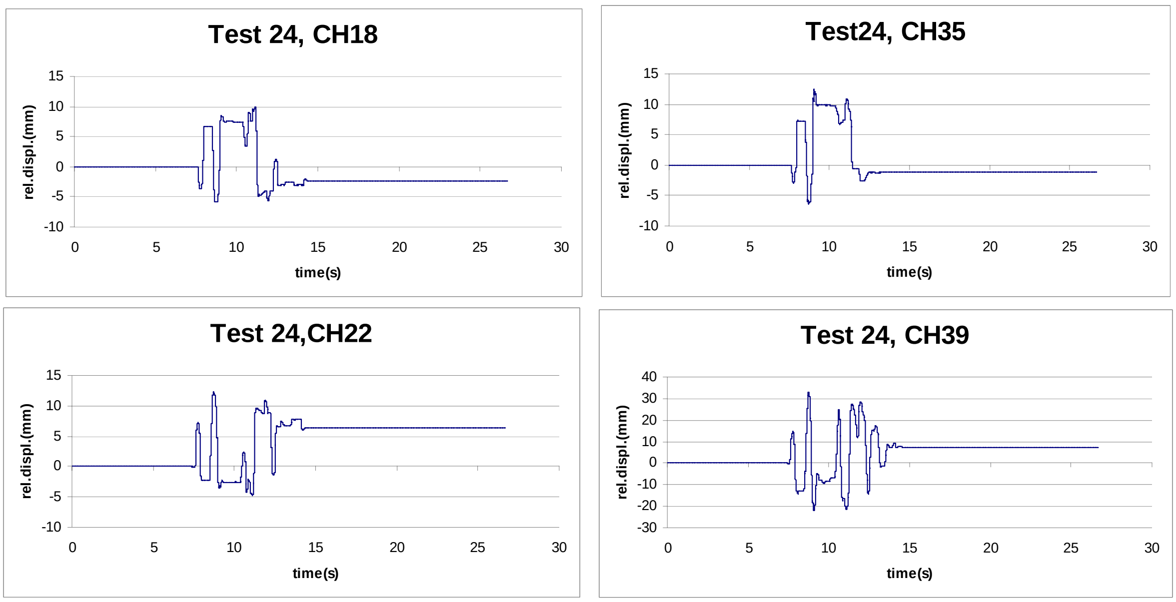

Figure 11. Slipping between the glass and the wooden frame during the Kobe earthquake, test 24

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