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Shaking table test of wooden building models for structural identification

Ahmet C. Altunışık*

Department of Civil Engineering, Karadeniz Technical University, Trabzon, Turkey

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Abstract. In this paper, it is aimed to present a comparative study about the structural behavior of tall buildings consisting of different type of materials such as concrete, steel or timber using finite element analyses and experimental measurements on shaking table. For this purpose, two 1/60 scaled 28 and 30-stories wooden building models with 40×40 cm and 35×35 cm ground/floor area and 1.45 m-1.55 m total height are built in laboratory condition. Considering the frequency range, mode shapes, maximum displacements and relative story drifts for structural models as well as acceleration, displacement and weight limits for shaking table, to obtain the typical building response as soon as possible, balsa is selected as a material property, and additional masses are bonded to some floors. Finite element models of the building models are constituted in SAP2000 program. According to the main purposes of earthquake resistant design, three different earthquake records are used to simulate the weak, medium and strong ground motions. The displacement and acceleration time-histories are obtained for all earthquake records at the top of building models. To validate the numerical results, shaking table tests are performed. The selected earthquake records are applied to first mode (lateral) direction, and the responses are recorded by sensitive accelerometers. Comparisons between the numerical and experimental results show that shaking table tests are enough to identify the structural response of wooden buildings. Considering 20%, 10% and 5% damping rations, differences are obtained within the range 4.03-26.16%, 3.91-65.51% and 6.31-66.49% for acceleration, velocity and displacements in Model-1, respectively. Also, these differences are obtained as 0.49-31.15%, 6.03-6.66% and 16.97-66.41% for Model-2, respectively. It is thought that these differences are caused by anisotropic structural characteristic of the material due to changes in directions parallel and perpendicular to fibers, and should be minimized using the model updating procedure.

Keywords: experimental measurement; finite element analysis; shaking table; wooden building

1. Introduction

Timber is an important structural material, which has been used since ancient times for the construction of buildings, bridges, docks etc. Although the use of steel and concrete material have an increasing trend in the last century, the use of timber material continues significantly especially in forest abundant countries like northern Europe, USA, Canada, China and Japan. Due to some advantages such as low handling cost and environmentally friendly, these type of structures have rapidly increased in construction industry during last decades (Oudjene and Khelifa 2009).

Because of the fact that timber has anisotropic structural characteristics, the material properties change in directions parallel and perpendicular to fibers. This is the most distinguished feature of timber material. Timber elements are subjected to a process of classification in order to define proper classes and related mechanical values. The material properties depend on wood types, humidity content, irregular fibers, defects, and knots (Magnus 2008).

Timber has sufficient strength both tension and compression. Also, it has higher load carrying capacity per unit weight compared to reinforced concrete and steel structures. However, due to its low stiffness, the deflection controls must be done in design (Khelifa *et al.* 2015).

High strength-to-weight ratio makes wooden structures as a good choice for earthquake-resistant construction. When all structural members and details are designed and constructed correctly, these structures show excellent behavior under seismic loads. Also, these structures show good response under seismic loads due to low mass and ductile connections (Hummel and Vogt 2014). In addition, correctly constructed traditional stone-filled wooden structures display the sufficient response with little damages during some big earthquakes such as Turkey 1999, Greece 2003, Kashmir 2005 and Haiti 2010 (Champagne *et al.* 2014).

Finite element method has been widely used in civil engineering applications since 1950s. Static, dynamic, linear and nonlinear behavior of structures can be obtained and illustrated using this method. However, depending on some uncertainties such as material properties, boundary conditions and mesh size considered in the finite element model, the expected behaviour of the structure can be changed after construction. Therefore, the finite element model should be verified using experimental measurements to reach the accurate models and conclusions.

There are several experimental measurement techniques such as modal testing, real earthquake experiences, field tests, static tests, shaking table tests, semi-dynamic tests, etc. Beside other techniques, the shaking table tests ensure

*Corresponding author, Associate Professor
E-mail: ahmetcan8284@hotmail.com

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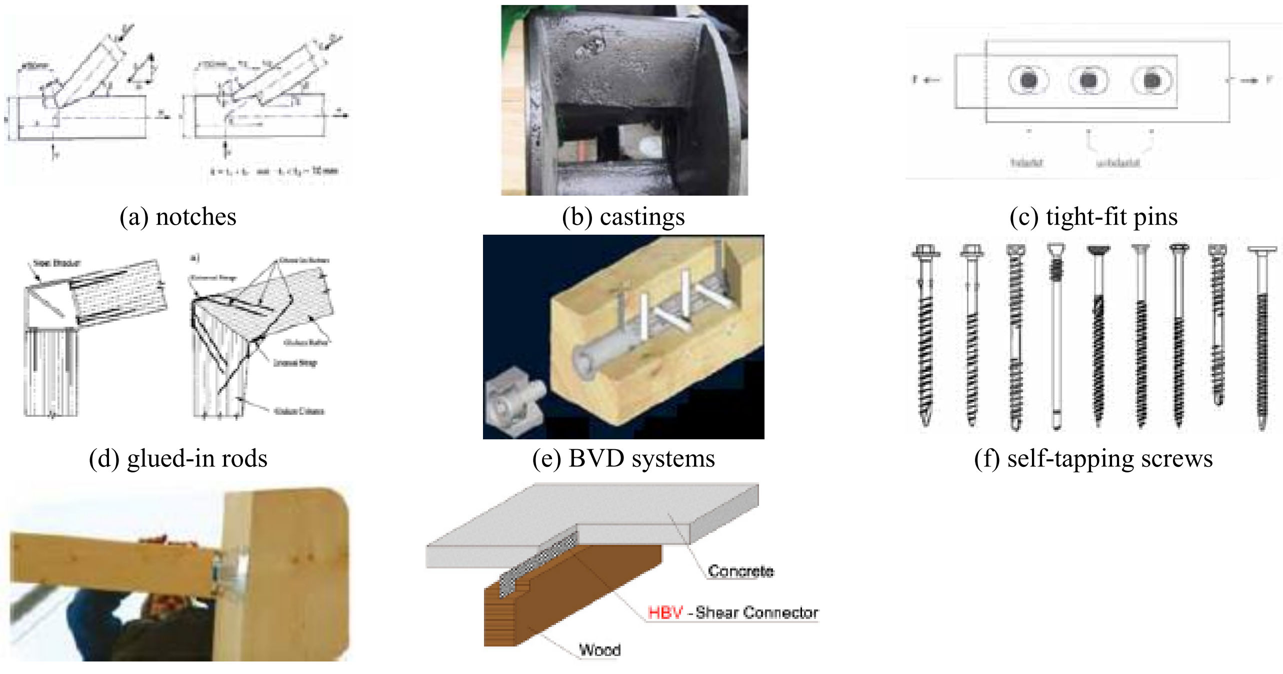


(a) notches (b) castings (c) tight-fit pins

(d) glued-in rods (e) BVD systems (f) self-tapping screws

(g) sherpa systems (h) HBV systems

Fig. 1 Some view from the innovative connectors

an opportunity to study on scale models in laboratory, and to obtain accurate responses in earthquake loads with suitable boundary conditions. So, there are some shaking tables with different size and movement capacity in different countries especially in Japan, USA and Europe.

Many studies have been performed on civil engineering structures to determine the structural responses using finite element analyses and experimental measurements using shaking table tests. Some researchers studied about the bridges and dam by finite element models, large-scale shaking table tests, sliding response (Tsai *et al.* 2007, Rochon-Cyr and Leger 2009, Phansri *et al.* 2010, Yang and Cheung 2011, Huang *et al.* 2014, Lie *et al.* 2014). The detailed investigations were carried out for seismic response of reinforced concrete frames and walls (Lestuzzi and Bachmann 2007, Yu *et al.* 2014). The structural behavior of steel structures was investigated to determine failure mechanism, base isolation effect and sloshing damper effect (Wu and Samali 2002, Hosseinzadeh *et al.* 2014). Some researchers evaluated the structural behavior and failure modes of different type of timber buildings using laboratory measurements, numerical analyses/simulations and shaking table tests (Buchanan *et al.* 2008, Ceccotti *et al.* 2013, Flatscher and Schickhofer 2015, Pozza *et al.* 2015). The recent studies have been published about the dynamic response of soil and masonry elements (Rabinovitch and Madah 2011, Zamani *et al.* 2011, Petrone *et al.* 2014, Wilson and Elgamal 2015). In spite of the fact that several studies can be found in the literature for civil engineering applications, very few studies have been addressed involving finite element analysis and shaking table tests of wooden buildings. This current paper is aimed to contribute some additional details about this subject.

2. Description of the buildings

To determine the structural response of wooden building models using experimental and numerical methods, two 1/60 scaled 28 and 30 stories models (Model-1 and Model-2) are constituted in laboratory conditions. Model-1 and Model-2 are designed to use of trade center and hotel, respectively. The models have 40×40 cm and 35×35 cm ground/floor area and 1.45 m-1.55 m total height. First floor height is considered as 10cm and the others are 5 cm for both models. The plates with 50×50 cm dimension with 2 cm thickness are placed the bottom of the models to take into account the raft foundation. The columns and cross-laminated timber wall system (CLT) are fixed on the foundation plates using installation holes and high strength adhesive.

The main problem of the timber structure is represented by the connection since the dynamic behaviour of a timber structure is largely due to the mechanical behaviour of the adopted connection system. The classical such as nails-screws, bolts, drift pins, lag screws, timber rivets, shear plates-split rings, truss plates, light gauge metals and the innovative connectors such as notches, castings, block gluing, tight-fit pins with bolts, ring nails, glued-in rods, BVD systems, WS systems, new age self-tapping screws, sherpa systems and HBV systems can be used for structural joints (Karsh 2013). Fig. 1 present the some view from the innovative connectors.

These systems are widely practiced on full-scale structure (Fig. 2). More detail information and application project detailing’s can be found in references (Karsh 2013).

The near collapse condition of timber wall systems can be defined both in design and modelling phase assuming a criterion based on the maximum displacement or distortion

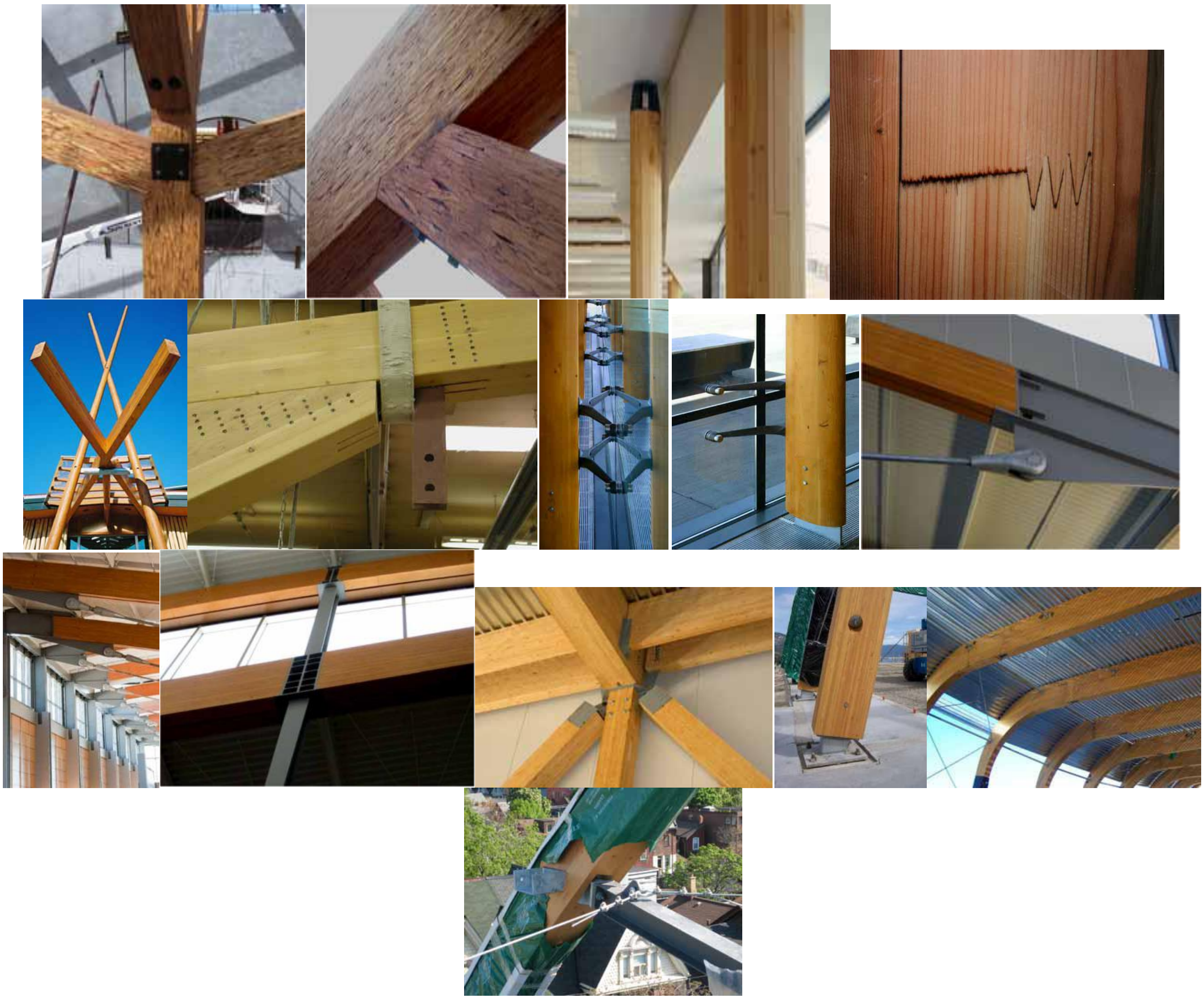


Fig. 2 Implementation of innovative connectors on full-scale structure (Karsh 2013)

Table 1 The structural properties of both buildings

Properties	Model-1	Model-2
Number of Stories	28	30
Total Weight	1260 gr	1092
Total Height	145 cm	155 cm
Used Area	29965 cm^2	35019 cm^2
Base Area	40×40 cm	35×35 cm
Section Properties		
Column	6×6 cm	6×6 cm
Beam	3×6 cm	3×6 cm
Cantilever	Variable 3×3 cm to 3×6 cm	3×3 m
CLT Wall	6×0.3 cm	Variable 6×0.3 cm to 3×0.3 cm
Stability	3×6 cm	3×3 m

Table 2 The mechanical properties of Balsa material used for both building

Mechanical Properties	Model-1 and Model-2
Nominal density	155 kg/m3
Compression Strength	14.1 MPa
Compression Modulus	4376 MPa
Tensile Strength	12.6 MPa
Tensile Modulus	3347 MPa
Shear Strength	3.1 MPa
Shear Modulus	189 MPa

capacity. Various limits of near collapse condition can be imposed as first collapse of a connection element or the achievement of an inter-storey drift. Different type adopted connection systems can be applied to structural models such as hold-down-foundation, angle bracket-foundation, screw-vertical joint, inclined screw-foundation and etc. (Ceccotti 2008, Polastri *et al*. 2014, Gavric *et al*. 2015, Pozza *et al*. 2015, Pozza *et al*. 2016).

All connection points such as columns-beams, CLT wall-beam, beam-bracing etc. are constructed using special details to ensure more stability. Considering the frequency range, mode shapes, maximum displacements and relative drifts for structural models, as well as acceleration,

(a) Model-1 (b) Model-2

Fig. 3 Some views of the wooden building models

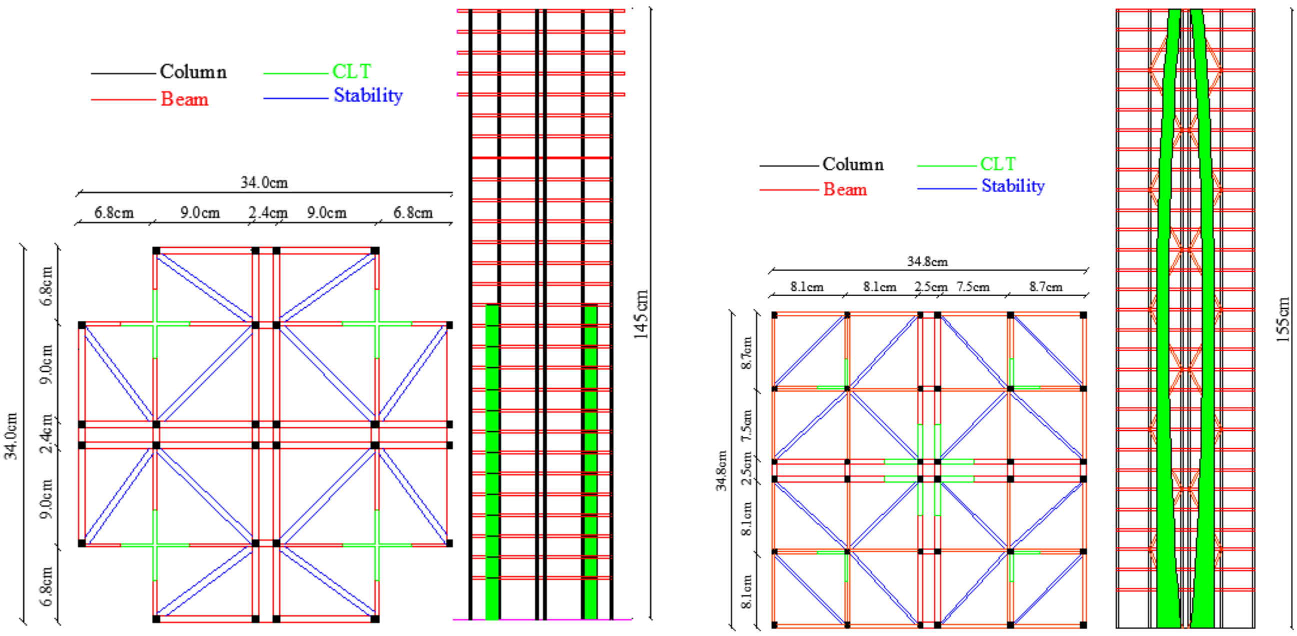
displacement and weight limits for shaking table, balsa is selected as a material property and additional masses are bonded to some floors to obtain the typical building response. Some views of the models are shown in Fig. 3. The plan and section drawings for both models are shown in Fig. 4. Also, the structural properties of both buildings with detailed information about the section properties of all structural members such as columns, beams, walls and stability members are presented in Table 1. Table 2 presents the mechanical properties of Balsa materials.

3. Shaking table tests

In the experimental measurements, the shaking table tests are performed on both wooden building models using three different earthquake ground motion records. The shaking table has 50×50cm table area and ±20cm lateral displacements capacity in one direction. To attain the vibration signals and conversion of these responses to displacements and accelerations, Testbox and Sensobox software are used. The view of shaking table with related software, data logger and accelerometers are shown in Fig. 5. Some technical properties of the table are given in Table 3.

During the experimental measurements, three different earthquake records are used to represent the weak, medium and strong ground motions, respectively. The occurrence probabilities of these earthquakes in 50 years are 50%, 10% and 2%, respectively. The acceleration, velocity and displacement time-histories of these earthquake records are given in Figs. 6-8. As seen in the figures, although the second acceleration record is very short (9.091 s), the peak values shows a sudden increasing trend. In this paper, the author aimed to investigate and evaluate how the wooden building models behave due to his effect. The peak values of acceleration, velocity and displacements are summarized in Table 4. Baseline correction and filtering (bandpass filter configuration using Butterworth filter type in linear baseline) is applied on all acceleration records to obtain more suitable and acceptable velocities and displacements results, and to avoid the unexpected increasing trend with time.

During the measurements, the scaled wooden building models are fixed to the shaking table's upper face using some clamps to prevent the movements. 1.25 kg additional masses are bonded to each 15 cm (three floors) to consider



(a) Model-1 (b) Model-2

Fig. 4 The plan and section drawings for both models

Table 3 Technical properties of shaking table

Properties	Model-1
Capacity	±1 g (100 kg) and ±2 g (50 kg)
Max. Power	100 N
Max. Velocity	500 mm/sn
Frequency Range	±80 mm-1 Hz; ±2 mm-10 Hz; ±0.4 mm-20 Hz
Sensibility	411counts/mm

Table 4 The peak values of acceleration, velocity and displacements of all earthquakes

Properties	Earthquakes		
	Weak	*Medium*	*Strong*
Time	26.63 s	9.091 s	35.866 s
Max. Acceleration	3.4180 m/s^2	8.2655 m/s^2	15.4112 m/s^2
Min. Acceleration	-2.5708 m/s^2	-5.7740 m/s^2	-13.8301 m/s^2
Max. Velocity	139.54 cm/s	278.56 cm/s	384.42 cm/s
Max. Displacement	15.63 cm	21.78 cm	28.72 cm

Fig. 5 View of shaking table including data logger and accelerometers

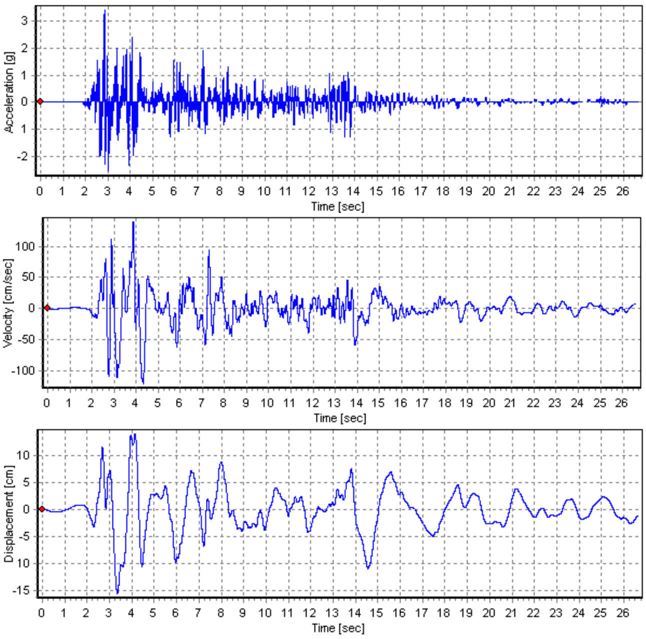


Fig. 6 Acceleration, velocity and displacement time-histories of weak earthquake

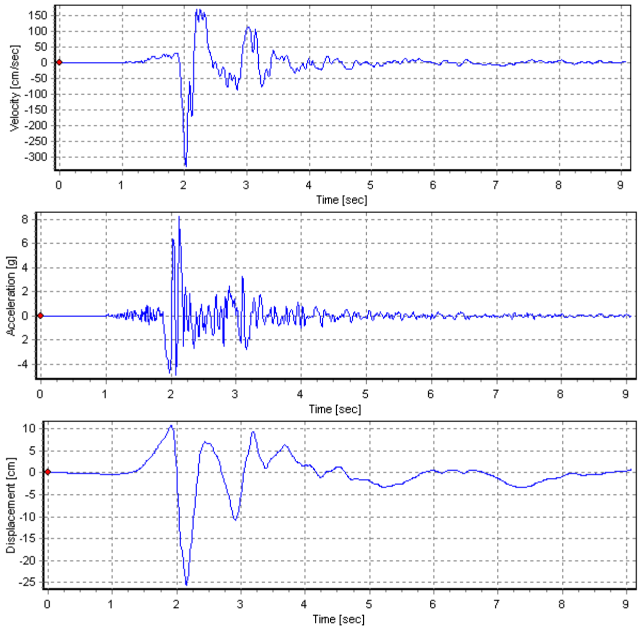


Fig. 7 Acceleration, velocity and displacement time-histories of medium earthquake

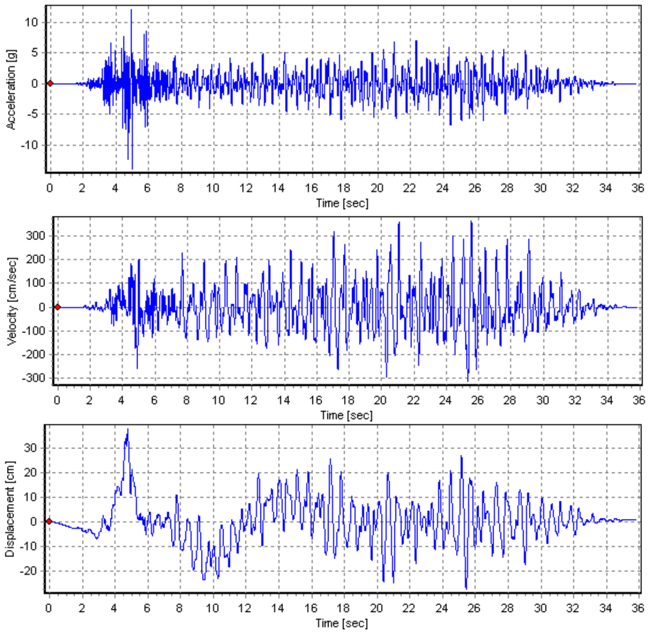
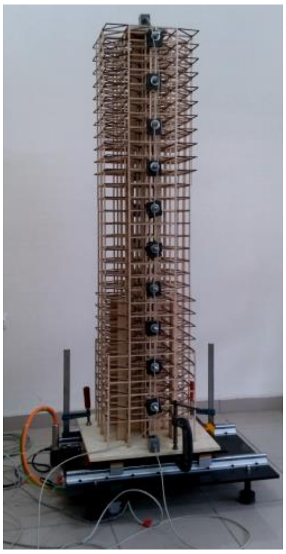


Fig. 8 Acceleration, velocity and displacement time-histories of strong earthquake

Table 5 Shaking table test results under all earthquake records for Model-1 and Model-2

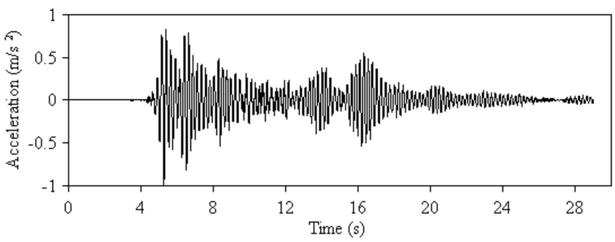
Building Models		**Measurement Results**		
		Acceleration (m/s^2)	*Velocity* (cm/s)	*Displacement* (mm)
Model 1	*Weak*	9.801	35.13	7.43
	Medium	18.819	49.60	10.16
	Strong	26.114	97.26	14.89
Model 2	*Weak*	10.94	40.25	7.92
	Medium	26.84	55.40	15.97
	Strong	38.62	107.16	25.47

the rigid diagram effect. Two sensitive accelerometers are located on the base and top of the building models to evaluate the both input forces and responses. Some views of the tests are shown in Fig. 9. Table 5 presents the shaking table test results under all earthquake records for Model-1 and Model-2, respectively. Figs. 10-12 show the acceleration, velocity and displacement time-histories obtained from the top points of wooden building models.

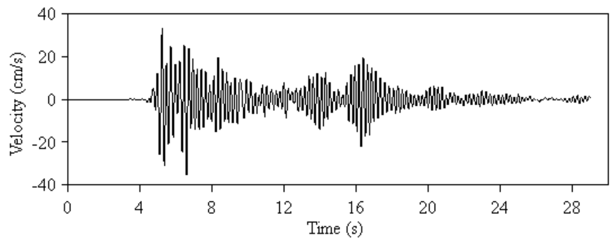


(a) Model-1 (b) Model-2

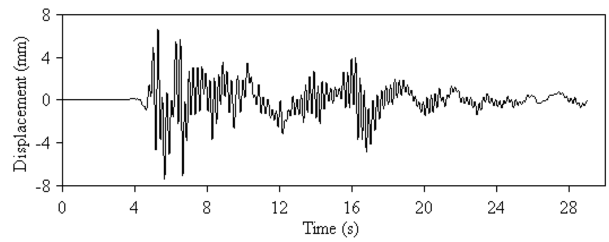
Fig. 9 Some views from the shaking table tests for Model-1 and Model-2



(a) Acceleration time-histories

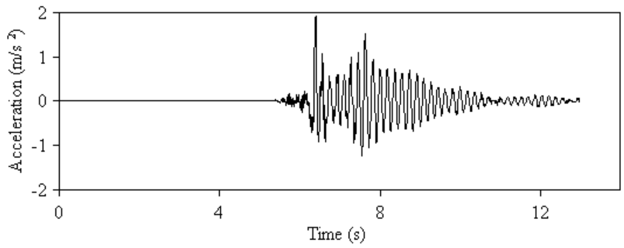


(b) Velocity time-histories

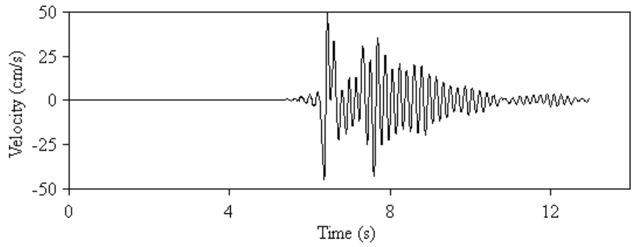


(c) Displacement time-histories

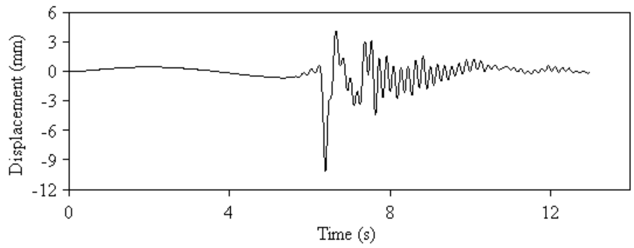
Fig. 10 Acceleration, velocity and displacement time-histories for weak earthquake



(a) Acceleration time-histories

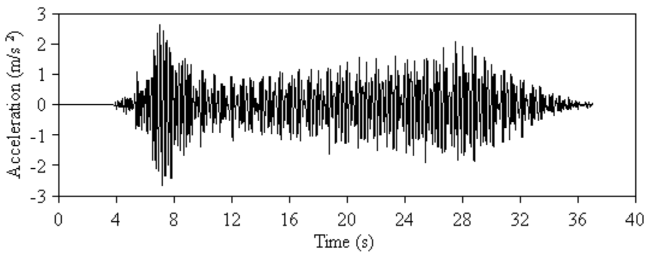


(b) Velocity time-histories

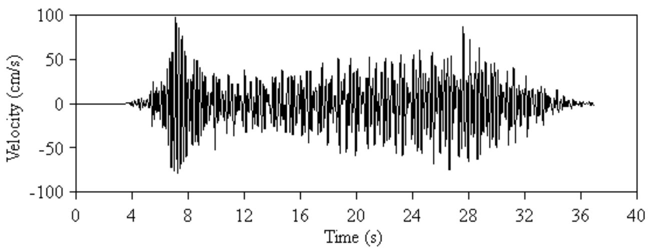


(c) Displacement time-histories

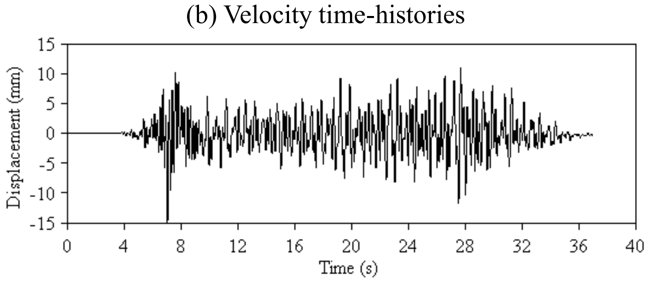
Fig. 11 Acceleration, velocity and displacement time-histories for medium earthquake



(a) Acceleration time-histories

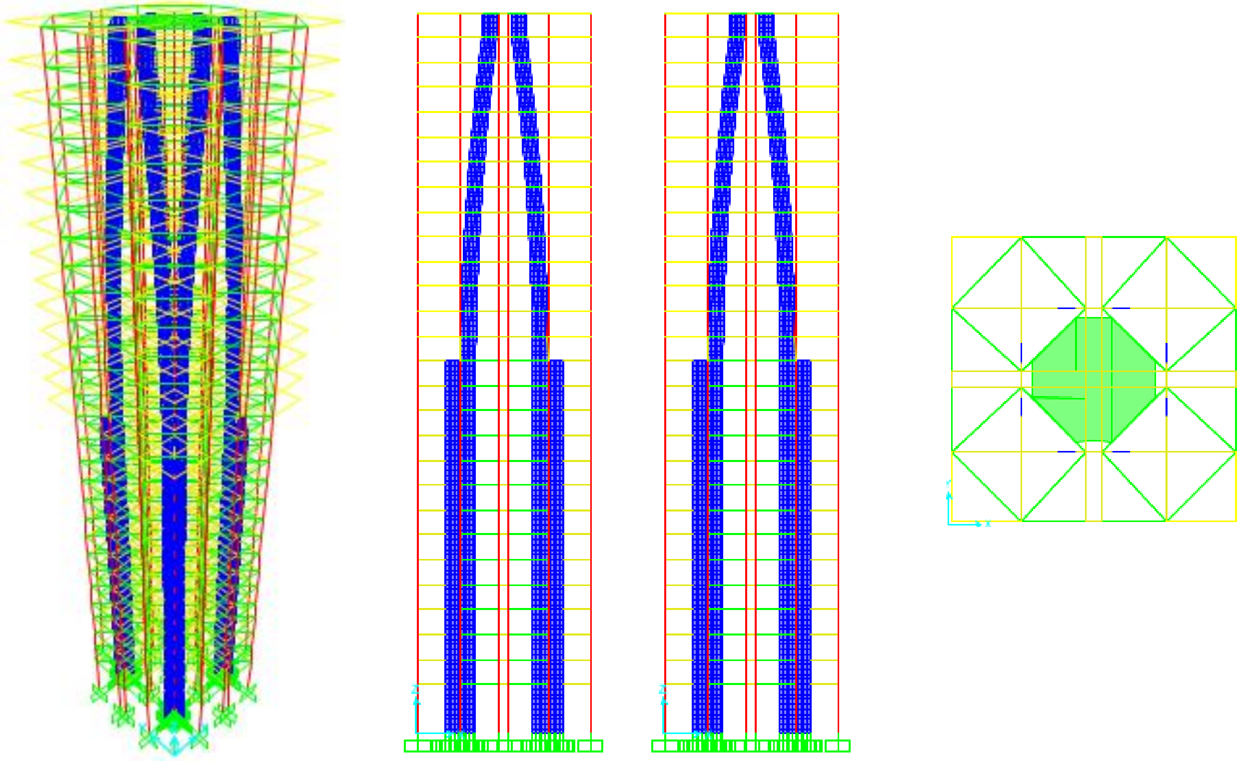


(b) Velocity time-histories

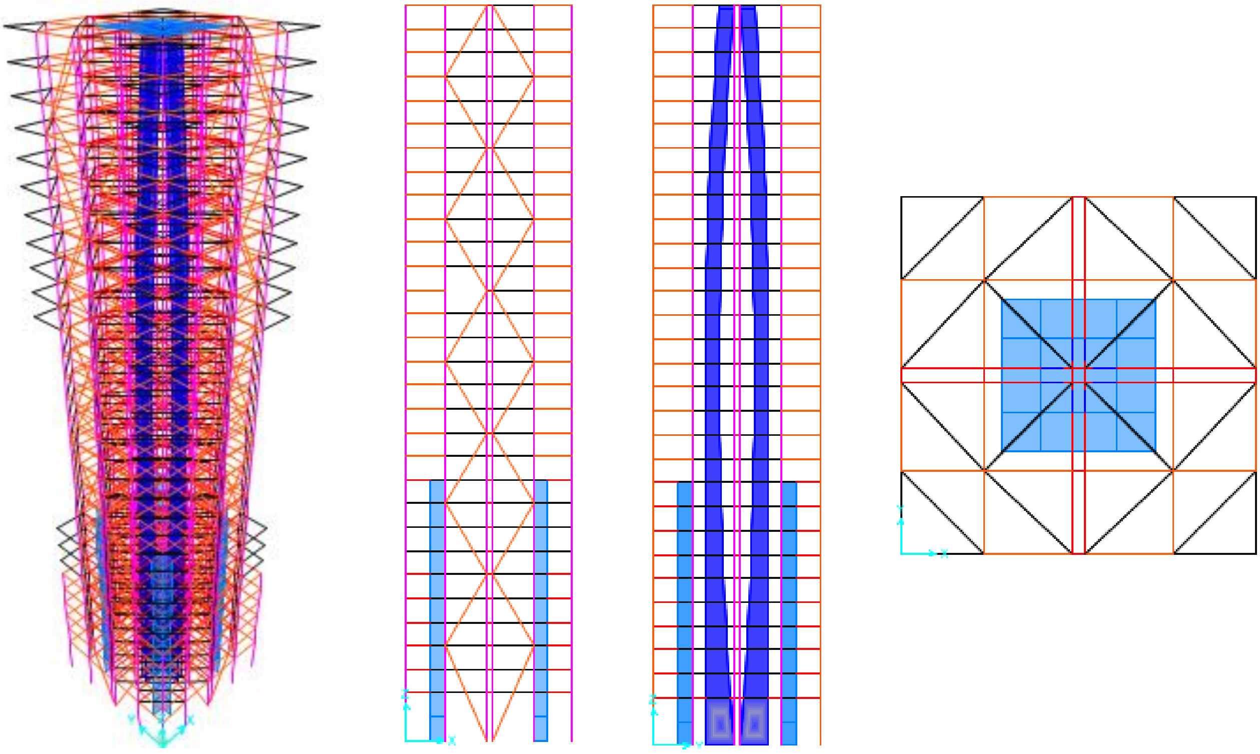


(c) Displacement time-histories

Fig. 12 Acceleration, velocity and displacement time-histories for strong earthquake



(a) Model-1



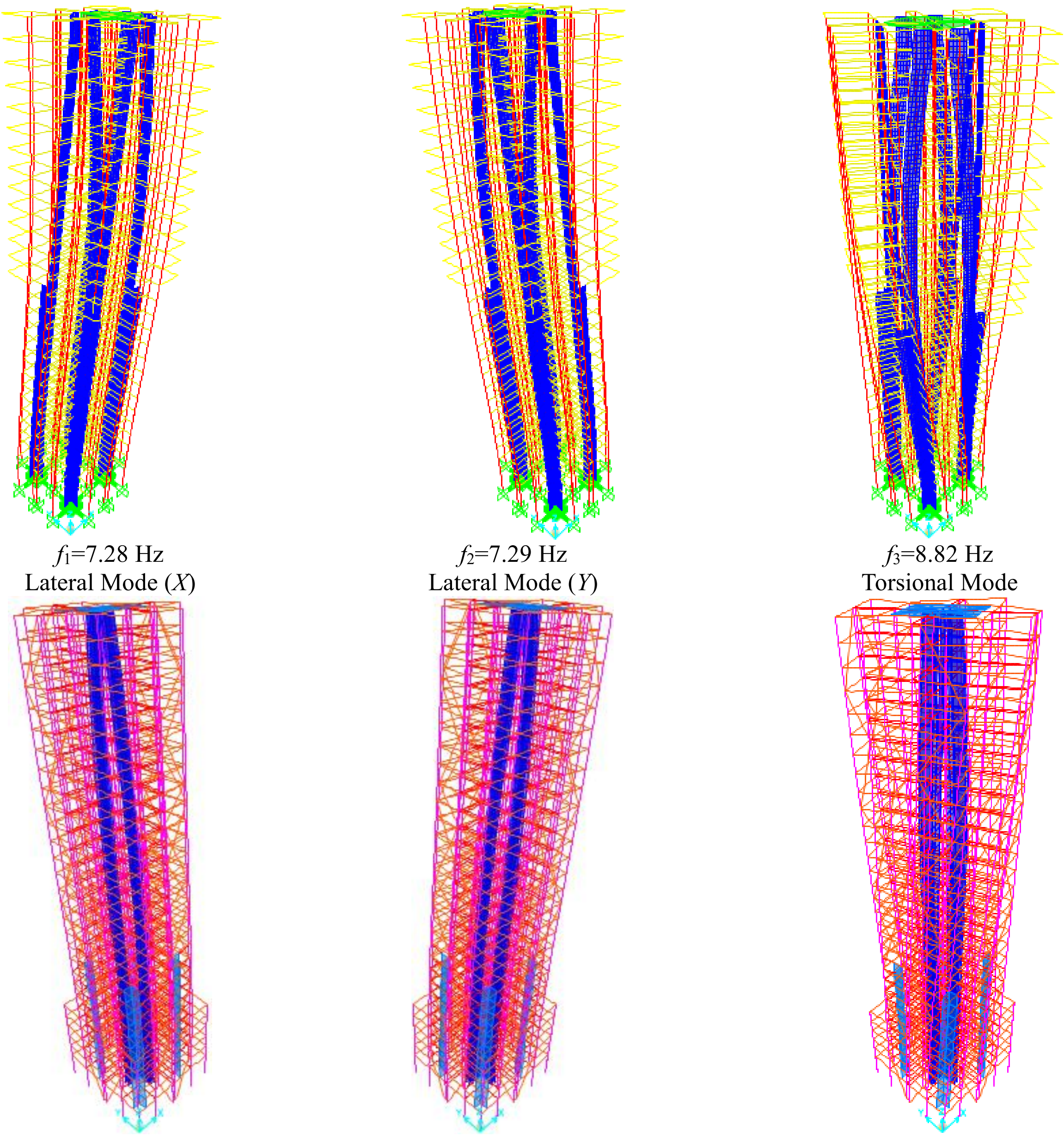
(b) Model-2

Fig. 13 Finite element models of the wooden building models

4. Finite element modeling

Three dimensional linear finite element models of the wooden building models are developed using the commercial software package SAP2000 (2015) to obtain the modal parameters such as frequencies, mode shapes and dynamic responses. The finite element model has the same geometry and reinforcement layout with the building model mentioned in section 2.

In the finite element models, the columns and beams are



f_1=7.28 Hz Lateral Mode (*X*) | f_2=7.29 Hz Lateral Mode (*Y*) | f_3=8.82 Hz Torsional Mode

f_1= 5.33Hz Lateral Mode (Y) | f_2= 5.41Hz Lateral Mode (X) | f_3= 8.37Hz Torsional Mode

Fig. 14 Numerically calculated first three mode shapes of the wooden buildings

modelled using beam elements, CLT walls are represented by shell elements. The additional masses are added as point loads at special contact surfaces. The mass source option is activated to calculate the masses of these additional loads in the modal analyses. The fixed restrains are assigned at the end of the base points. Some views of the models are shown in Fig. 13. The material properties taken into consideration for analyses are summarized in Table 6.

The modal analyses are performed and first ten mode shapes are obtained for both models. The mode shapes and related frequencies are given in Fig. 14. It can be seen from the figure that the first and second modes are lateral (7.28 Hz and 7.29 Hz for Model-1; 5.33 Hz and 5.41 Hz for Model-2) and the third mode is torsional modes (8.82 Hz and 8.37 Hz). When the mode shapes are compared with

Table 6 Material properties used in the finite element analyses

Parameters	Values
Modulus of Elasticity	2E9 N/m^2
Mass per Unit Volume	180.5 kg/m^3
Poisson Ratio's	0.23
Damping Ratios	20%, 10%, 5%

each other and literature, it is seen that these models can be successfully used to represent the similar full scale buildings (concrete, steel, wooden, masonry etc.).

It is seen from the Fig. 4 that the wooden building models have same rigidity in *x* and *y* direction due to

Table 6 Comparison of the finite element analyses and shaking table test results

Models / Earthquakes / Responses			Finite Element Analysis			Shaking Table Test	Max. Dif. (%)
			20% Damping	10% Damping	5% Damping		
Model-1	Weak	*Acceleration (m/sn²)*	7.237	9.32	10.84	9.80	4.09-26.16
		Velocity (cm/s)	12.28	15.11	29.33	35.13	16.68-65.51
		Displacements (mm)	2.49	3.17	5.26	7.430	29.20-66.49
	Medium	*Acceleration (m/sn²)*	17.69	19.58	22.90	18.82	4.03-6.00
		Velocity (cm/s)	32.05	41.80	51.54	49.60	3.91-35.38
		Displacements (mm)	6.511	9.28	11.66	10.16	8.66-35.92
	Strong	*Acceleration (m/sn²)*	23.30	24.15	29.09	26.11	7.50-10.78
		Velocity (cm/s)	39.71	56.92	76.20	97.26	21.65-59.17
		Displacements (mm)	8.78	13.19	15.83	14.89	6.31-41.03
Model-2	Weak	*Acceleration (m/sn²)*	8.33	10.26	11.49	10.94	5.02-23.86
		Velocity (cm/s)	13.42	17.20	31.03	40.25	22.91-66.66
		Displacements (mm)	2.66	3.43	5.54	7.92	30.05-66.41
	Medium	*Acceleration (m/sn²)*	19.92	26.97	30.90	26.84	0.48-25.78
		Velocity (cm/s)	35.56	47.57	58.74	55.40	6.03-35.81
		Displacements (mm)	7.35	10.57	13.26	15.97	16.97-53.98
	Strong	*Acceleration (m/sn²)*	26.59	38.04	41.90	38.62	1.50-31.15
		Velocity (cm/s)	43.20	64.36	86.50	107.16	19.28-59.69
		Displacements (mm)	9.46	14.36	19.18	25.47	24.69-62.86

symmetry. For this reason, after the modal analyses, first natural frequencies and related mode shapes are obtained as very close each other. The difference (very little and within the acceptable limits) arises from the construction errors.

The linear transient analyses are carried out for the earthquake ground motion records considered. These records are applied to the first mode directions. Change in accelerations and displacements by the height of building models with maximum time-histories is obtained in detail. The results are given in Table 6 with the comparison of shaking table tests. It can be seen that shaking table tests are enough to identify the structural response of wooden buildings under different load cases and combination. Considering 20%, 10% and 5% damping rations, differences are obtained within the range 4.03-26.16%, 3.91-65.51% and 6.31-66.49% for acceleration, velocity and displacements in Model-1, respectively. Also, these differences are obtained as 0.49-31.15%, 6.03-6.66% and 16.97-66.41% for Model-2, respectively. It is thought that these differences are caused by anisotropic structural characteristic of material due to changes in directions parallel and perpendicular to fibers, and should be minimized using the model updating procedure.

5. Conclusions

This paper presents a comparative study about the structural behavior of tall buildings consisting of different type of materials such as concrete, steel or timber using finite element analyses and experimental measurements on shaking table. For this purpose, two 1/60 scaled 28 and 30-stories wooden building models are built in laboratory condition. Considering the frequency range, mode shapes, maximum displacements and relative story drifts for structural models as well as acceleration, displacement and weight limits for shaking table, balsa is selected as a material property to obtain the typical building response. The following conclusions can be drawn from the study:

- Experimental measurements are conducted on the shaking table using weak, medium and strong ground motion records. The occurrence probabilities of these earthquakes in 50 years are 50%, 10% and 2%, respectively.
- From the shaking table tests, maximum accelerations, velocities and displacements are obtained between 9.801-26.114 m/s^2, 35.13-97.26 cm/s, 7.43-14.89 mm for Model-1; 10.94-38.62 m/s^2, 40.25-107.16 cm/s, 7.92-25.47 mm for Model-2. It is seen that Model-1 has more rigidity and energy observation capacities thanks to its structural design and carrier system.
- The finite element models of the buildings are constituted and modal analyses are performed to obtain

the first ten mode shapes. It can be seen that the first and second modes are lateral (7.28 Hz and 7.29 Hz for Model-1; 5.33 Hz and 5.41 Hz for Model-2) and the third mode is torsional modes (8.82 Hz and 8.37 Hz). As stated above, Model-1 has more rigidity and energy observation capacities. When the mode shapes are compared with each other and literature, it is seen that the structural behavior of these models are very similar to full scale buildings (concrete, steel, wooden, masonry etc.).

• The linear transient analyses are carried out for the earthquake ground motion records considered. These records are applied to first mode directions. The changing of accelerations and displacements by the height of building models with maximum time-histories is obtained in detail.

• The experimentally and numerically identified results are compared with each other. Considering 20%, 10% and 5% damping rations, differences are obtained within the range 4.03-26.16%, 3.91-65.51% and 6.31-66.49% for acceleration, velocity and displacements in Model-1, respectively. Also, these differences are obtained as 0.49-31.15%, 6.03-6.66% and 16.97-66.41% for Model-2, respectively.

• It is thought that these differences are caused by anisotropic structural characteristic of material due to changes in directions parallel and perpendicular to fibers, and should be minimized using the model updating procedure.

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