Earthquake Resistant Multi Storey Structures

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Earthquake Resistant Multi Storey Structures

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Summary: *This paper provides an overview on some experimental and analytical activities conducted by the authors, on a balsa wood scale structures that was designed for a Seismic Design Competition (SDC) organized by Earthquake Engineering Research Institute from USA. Highlights are presented in the paper focusing on experimental researches including the design, the analytical approach, and the laboratory tests executed on shaking table facility and equipment available at the Technical University of Cluj-Napoca.*

Keywords: *Balsa wood structure, Shaking table, Time history, Experimental testing, Laboratory.*

INTRODUCTION

International annual Seismic Design Competition (SDC) held in USA requires the design of a 3D multi-story (from 15 to 28 story) structure that is subjected to several recorded (and scaled down) and artificially generated earthquakes [1]. No failure is a fundamental criterion for winning the competition. Current study is an extract of the theoretical and experimental job carried out by the TUCN team that qualified for the final phase (Seattle, February 2013) of the competition. For designing the building several aspects have been taken into consideration, such as architecture, the environment, financial costs (investment/maintenance), all of which were subordinated to fundamental principles of seismic design.
The resulting structure has a two axis in plane symmetry, and it’s based on a bundle tube concept, consisting of four 3D substructures located in the four corners. Each substructure is made up of 3D one bay frame that creates an open space inside, allowing a large freedom of inside arrangement at every level.
For the theoretical study of the structure in what regards its seismic response, several scaled down earthquakes have been used: Northridge 1990, El Centro 1940, DAVIS - artificially generated earthquake (ground acceleration=1.57g).
The dynamic model considered for this structure is the classical lumped mass vertical cantilever. Computed parameters refer to natural period of vibrations T_1, seismically induced response (lateral displacement and accelerations, base shear).
The experimental studies focused on recording the seismic responses in lateral displacement and acceleration, objective that has been achieved using a laboratory shaking table [2] equipped with digital transducers and recorders.
A highly acceptable accuracy could be noted of experimental and theoretical results. Obtained results constituted the bases of a beforehand compulsory assessments of seismic response at the final stage of the SDC
For a more accurate modelling of real loading, dead loads that act upon the structure have been represented with steel bars, mounted upon the structure at H/10 distance between them and perpendicular placed towards earthquake action direction (Fig.1).

Fig. 1: Scaled structure loading pattern and orientation

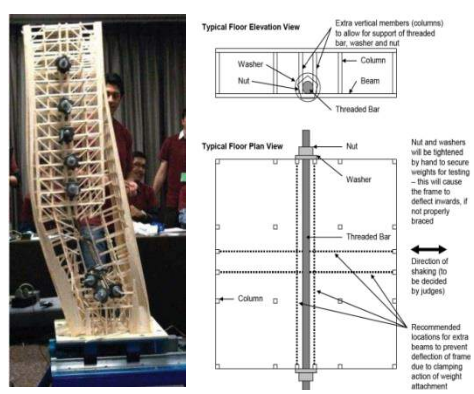

Fig. 2: Steel bar weights

These additional loads have a weight of 1.18 kg (Fig. 2) each except the one used for the roof top that was a 1.59 kg weight.
The proposed scaled structure, loaded with the dead load (steel bars) will be subjected to three ground motions on a shaking table, these representing three scaled earthquakes: GM1 (Northridge 1994) and GM2 (El Centro 1940) – first two earthquakes and the third one, GM3 much stronger earthquake the first two (having a_g=1,57g), that is artificially generated.
The essential criterion is a non-collapse requirement during the three tests. Another criterion is the cost-efficiency of the structure, obtained by evaluating the structural state after testing the scaled model. The evaluation is done to determine the retrofit cost (depending on the top lateral displacement and acceleration values recorded), which add to the investment costs (which are assumed to be divided for 100 years). The profit was obtained by reducing the costs from the income obtained by renting space in the building. Another important criterion was prediction accuracy for top lateral acceleration and displacement that will be recorded during the competition.
For the construction of the balsa model a few conditions were imposed by the competition organizers:

-storey height should be 5cm, and 10 cm respectively for floor and 10 storey;
-structure footprint should be no greater than 38 cm x 38 cm;
-rentable floor area should be less than 11.684 cm2
-balsa wood structure together with the base plate should weigh less than 2.2 kg.

Taking into consideration all these factors it results a final structure symmetrical on two orthogonal directions, having four frame substructures placed in all the four corners, joined together with a central core and seismically protected by a fishing net that has a dissipative role.

1. ARHITECTURE

The main objective described in the brief of the Seismic Design Competition was to submit a project for a multi-storey commercial office building in Seattle, WA, that would take the place which is currently occupied by the Seattle Space Needle, the most important architectural challenge being to design a new iconic building for the city.
Another important demand was to conceive a cost that is designed for seismic loading and allows a generous amount of natural daylight to enter the building for sustainability purposes.
A mixed group of architecture [3] and engineering undergraduate students were selected to work together on this hands-on project designing and constructing a highly economical frame building to resist seismic loading, thus promoting a interdisciplinary approach that lead to a higher complexity project with increased chances of success.
At this early phase of design a very close co-operation was encouraged. Developing good communicational skills and assuring a continuous interaction between team members was the main objectives of the design workshops.
Taking into consideration all the constrains of the competition brief, several architectural models were developed based on desired traits like architectural iconicity, economic and ecological sustainability combined with several earthquake design related issues (mainly regarding the influence of different spatial configuration upon the seismic response of a building). The proposed architectural concepts (Fig. 3) were analyzed for obtaining a feedback regarding their structural feasibility

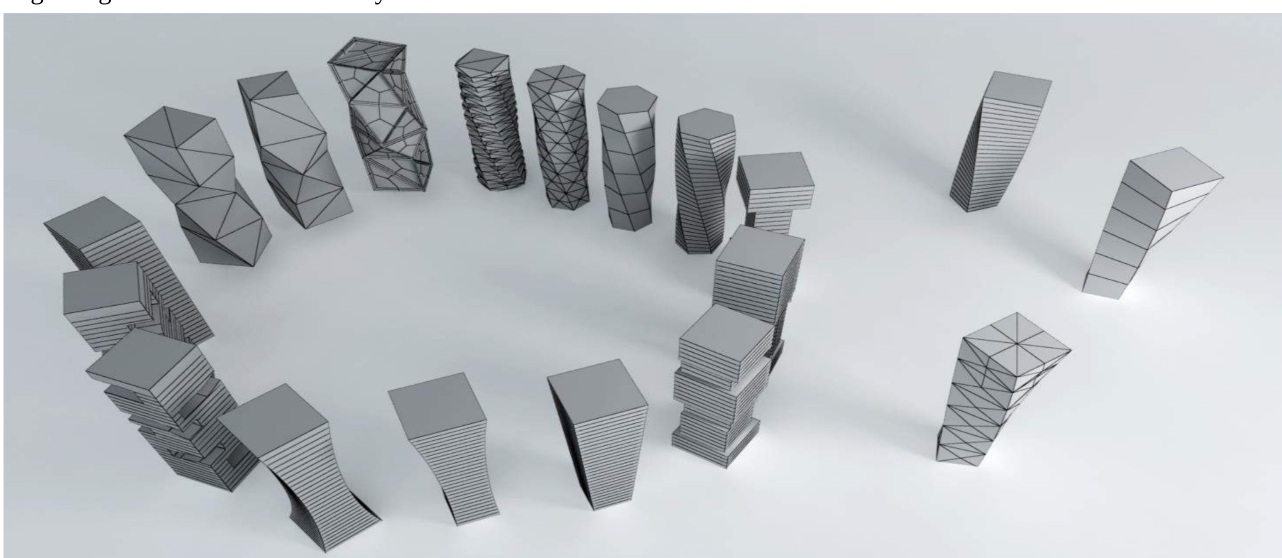

Fig. 3: Different architectural concepts

The effect of the shape, height and mass of buildings was studied and the different architectural concepts, such as recessed volumes, vertical planar discontinuity, uniform or eccentric mass were researched and discussed thus obtaining the first feasible concept.
As a result of the different morphological studies, a highly symmetrical configuration was selected (Fig. 4). Having a two-axis in plane and in elevation symmetry, this structure had the most favorable predicted behavior during the seismic loading.

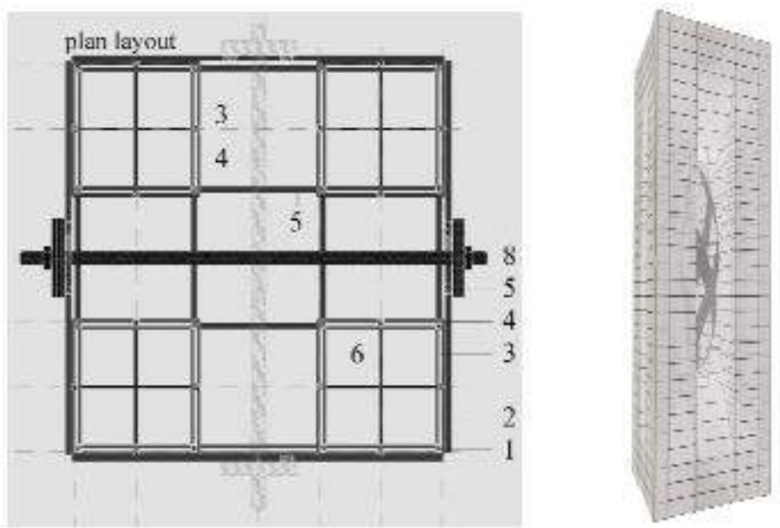

Fig. 4: Prototype

The structure also met all the architectural requirements regarding the function, quality and contextual relations, therefore it was submitted as a first design proposal. Being accepted by the competition board prototype was further developed, going through continuous improvements.

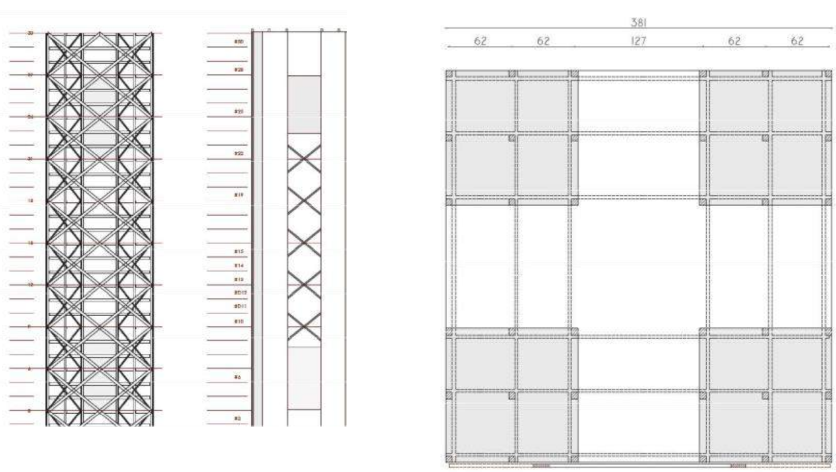

Fig. 5: Intermediary configuration

Several intermediary structures (Fig. 5) were designed, theoretically analyzed, build and tested on the shaking table equipment. For each structure the architectural requirements were verified and the lateral displacements and accelerations were recorded during the seismic loading.
These studies served as the basis of the structural and architectural improvements that consisted either of configurationally changes, or of smaller interventions like different load-bearing elements being added or subtracted in order to achieve the best mass (economic criteria) to seismic strength ratio.
The final solution (Fig. 6) was a result of all the modifications made on the intermediary structure designs and on the scaled model. The final design consists of four frame structures placed symmetrically around a central core. The four outer structures were designed to accommodate the office spaces (rentable area) and the central core as the main circulation area (vertical and horizontal access).

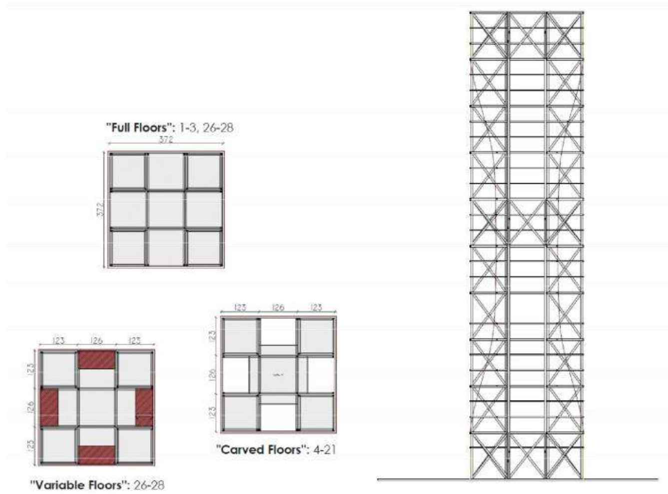

Fig. 6: Final layout and section

The mid-section of the layout is characterized by a seclusion that was proposed to increase the natural daylight intake of the building, thus the four corner structures have a constant vertical development, and the central core more dynamical and sculptural expression (Fig.7).

Fig. 7: Final rendering

From a structural point of view, the increasing of the lower levels area was meant to contribute to a better seismic response. From an economical point of view, splaying the upper part of the building made lots of sense, taking into consideration that the higher level offices are more expensive to rent and ensure increased annual revenue.

A cost-benefit analysis was carried out to determine the cost effectiveness of the proposed building. This was be done by balancing the revenue with the initial building cost and seismic cost. (Table 1)

NUMBER OF LEVELS			28
TOTAL FLOOR AREA		square inch	4660
BUILDING FOOTPRINT		square inch	214,50
STRUCTURAL MODEL WEIGHT		pound	2,202643
RENTABLE FLOOR AREA		REVENUE	ANNUAL REVENUE
	square inch	$/year/square inch	$/year
LEVEL 1-15	2383,50	125	297.937,50
LEVEL 16-24	1428	175	249.900,00
LEVEL 25-28	838,50	225	188.662,50
	4650		736.500,00
BUILDING COST		BLD. LIFE	ANNUAL BUILDING COSTS
	$	year	$/year
COST OF THE LAND	7.507.500	100	75.075,00
CONSTRUCTION	19.823.787	100	198.237,87
	27.331.287		273.312,87
EQUIPMENT COST	20.000.000		
ECONOMIC LOSS		RETURN PER.	ANNUAL SEISMIC COST
	$	year	$/year
GM1	2.756.574,22	50	55.131,48
GM2	18.436.679,07	150	122.911,19
GM3	19.990.483,28	300	66.634,94
			244.677,62
ANNUAL BUILDING INCOME		$/year	218509,51

Table 1: Cost-benefit analysis

2. STRUCTURAL ANALYSIS

Structural analysis [4, 5] has been done using SAP 2000 software. The designed model has the maximum height of 28 levels, for which the structural elements have the maximum dimensions allowed by the organizers.

All the materials used for the structure were modeled in the software analysis program. The density of balsa wood had values between 90 and 300 kg/m3, but for the actual structure construction, material that had closed density was used, and in the software analysis program a medium density of 150 kg/m was used.

SAP2000 structural modeling (Fig. 8) proved to be difficult to execute, due to the fact that the software is considering that the analyzed materials are homogenous and isotropic, a hypothesis that is not fulfilled especially when we are dealing with balsa wood.

An optimization of the first design was performed by introducing supplementary elements, by modifying the section of different elements, always taking into account the entire weight of the structure.

For the structural analysis a time-history type analysis was performed, using the three time-history functions (GM1, GM2, GM3) that were imposed by the rules of the competition. Following the analysis, different types of parameters were extracted, i.e. fundamental period of vibration, top lateral absolute acceleration (Fig.11, Fig. 12, Fig. 13), top lateral displacement (Fig. 14, Fig. 15, Fig. 16).[6]

Fundamental period of vibration varied for each structural model that was created and the values were between 0.06s and 0.11s. Due to the high rigidity of the structure a high probability of column failure in the base appeared. To overcome this failure supplementary bracings were placed in the base of the structure to redistribute the base shear to a greater area.

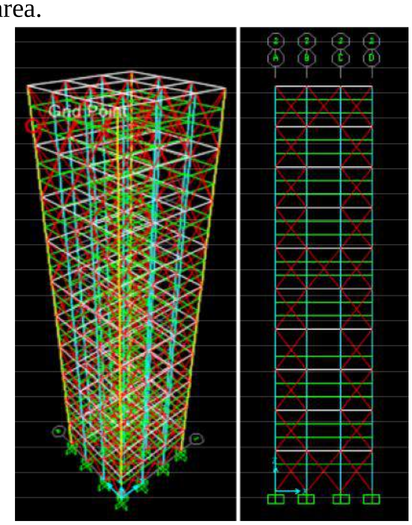

Fig. 8: Structural modelling

3. CONSTRUCTION STAGE

Four balsa wood (Fig. 9) scaled structures were constructed, from which, three were subjected to tests on the shaking table, and the fourth one, identical with the third, was tested only during the seismic design competition
For fabricate the elements out of balsa wood, a circular saw was used. For connecting the elements, fluid and superfluid glue was used, that was specially designed for this type of material,
The scaled structure was combined from four sub-assemblies, disposed in the four corners of the structure, joined together to a central core (Fig. 10). To optimize the construction period, and more than one team to be able to work, two stencils were build: one for the façades of the four exterior columns, and another for the façades of the central core. After the assembly of all the elements the fishing net was mounted on the exterior of the structure.

Fig. 9: Balsa wood

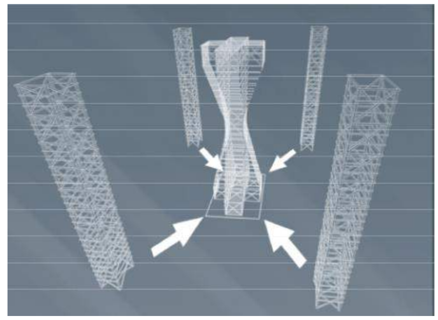

Fig. 10: Structural assembly

4. TESTING

For the laboratory testing, a shaking table produced by Quanser was used, that is able to work up to 2.5 g maximum acceleration. For acceleration recordings, accelerometers were used at the base and at the top of the structure, and for the displacement recording, displacement transducers were used, and were mounted also at the base and at the top of the structure.

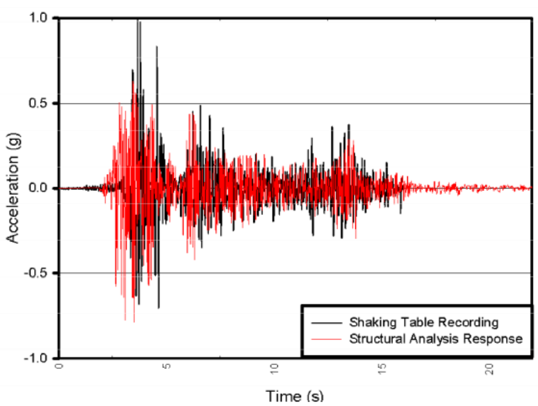

Fig. 11: GM 1 top lateral acceleration

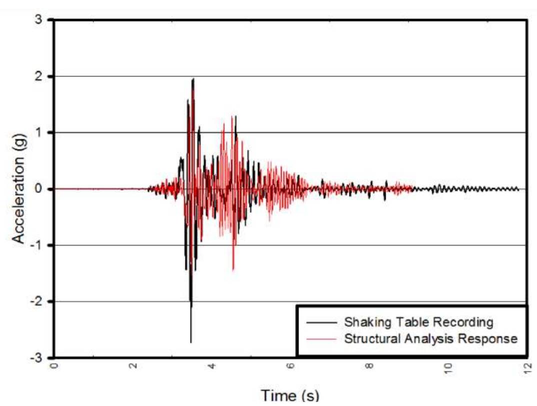

Fig. 12: GM 2 Top lateral acceleration

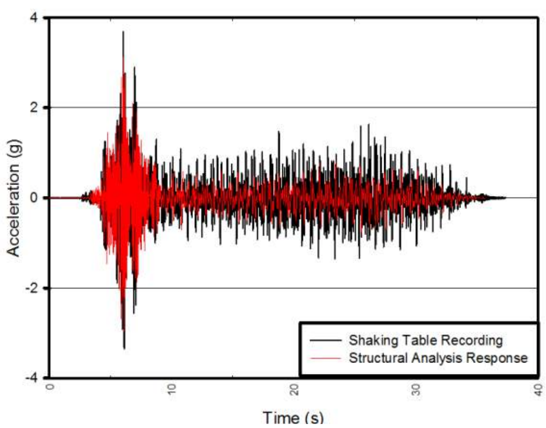

Fig. 13: GM 3 top lateral acceleration

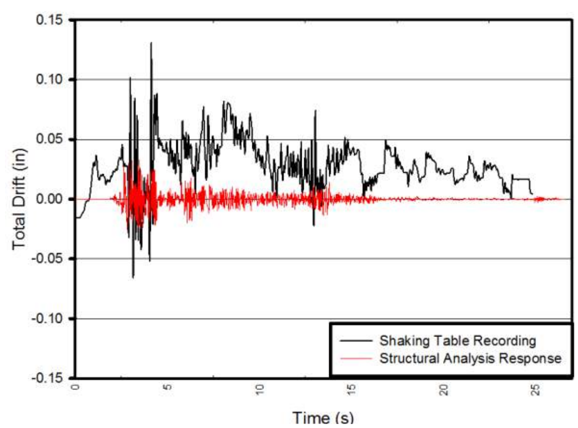

Fig. 14: GM 1 Top lateral displacement

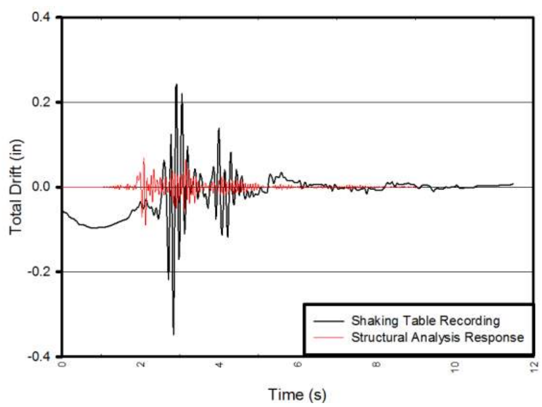

Fig. 15: GM 2 Top lateral displacement

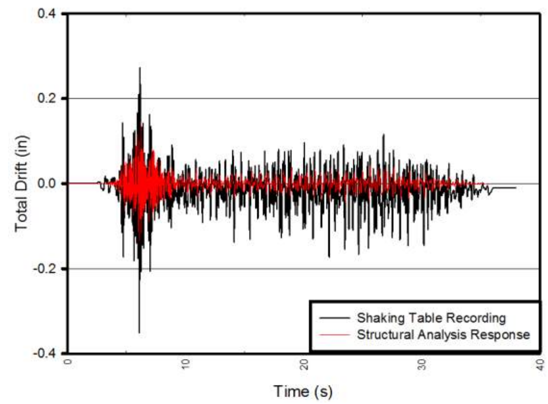

Fig. 16: GM 3 Top lateral displacement

The same three scaled accelerograms were used for laboratory testing as in software analysis. After the first two structures were tested, a structural failure due to base shear in the lower third of the structure was observed. Due to this type of failure, extra columns and extra bracings were mounted in the lower part for the last two structures.

5. CONCLUSION

The main objective - to design and construct a balsa wood structure that will satisfy all the technical and economical requirements imposed by the organizers – was successfully achieved. The structural architecture has the ecological concept imposed by the organizers through its carved shape that allows a natural lighting and ventilation of the entire structure and by maximum use of the entire rentable area.

The parameters that define the seismic response, that were obtained through both methods, analytical and experimental, and that were delivered to the organizers as predictions to the final behaviour of the structure, were very close to the actual values that were recorded during the competition(less than 5% error). The fact that the designed structure obtained points in all grading fields (structural, architectural, and prediction) proves the fulfilment of the UTC-N team objectives at SDC 2013.

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