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Similitude Distortion Compensation for a Small Scale Model of a Knee Braced Steel Frame

[1]Nouredine Bourahla and [2]Anthony Blakeborough

[1]*Department of Civil Engineering, University of Blida, Blida, Algeria*
[2]*Department of Engineering Science, University of Oxford, Oxford, UK*

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Corresponding Author:
Nouredine Bourahla
Department of Civil Engineering,
University of Blida, Blida,
Algeria
Email: nbourahla@univ-blida.dz

Abstract: The purpose of producing scaled physical models is to allow the assessment in the laboratory of the probable response of a structure to a prescribed loading. It is obviously of paramount importance to construct these models to reflect reality as accurately as possible. The problem encountered particularly for dynamic testing is that the similitude requirements are sometimes impractical. This paper presents the design details of 1:12 scale model of a ten storey Knee Braced Frame (KBF) for testing on a shaking table. The implications of imperfect similitude are investigated and a mass adjustment technique is used to compensate for the modeling distortion. The method used is successful in correcting the unsatisfied similitude conditions. The dynamic properties as well as the response parameters of primary interest, i.e., horizontal floor displacements, knee element ductility and the energy dissipation capacity of the small scale model are then within the range of true scale buildings.

Keywords: Knee Bracing System, Small Scale Modeling, Seismic Testing, Dimensional Analysis

Introduction

Any structural scaled model should be designed, tested and the results interpreted according to the similitude requirements that relate the model to the real structure. The similitude requirements are based upon the theory of modeling which can be derived from dimensional analysis of the physical phenomena involved in the behavior of the structure. In general structural modeling problems are mechanical, thus the measures of length, force and time are the most important. There are a number of formal techniques which involve setting up the appropriate dimensional equations (Sabnis *et al*., 1983). In the case of structural models, the scaling factors for length S_l and Modulus of Elasticity S_E are chosen and then all the other factors can be expressed as functions of S_l and S_E. When strength and post-yield response are important and gravity effects cannot be neglected, dynamic similitude theory dictates strict physical requirements that the model must satisfy.

In steel frame buildings the mass can often be assumed to be concentrated at floor level, permitting a simplification of the modeling constraints through artificial mass simulation. This technique involves the addition of structurally uncoupled mass to augment the density of the model and permits selection of a model structural material without regards for mass density scaling. This method was widely used in small scale steel frames (Dumanoglu and Severn, 1985; Li *et al*., 2006; Zhou and Li, 2010). In the so-called acceleration-based similitude law, in addition to the added mass, a compressed time scale is needed for performing the real-time dynamic tests because scale factors for mass and time correspond to S_l^2 and $S_l^{0.5}$ respectively. This is particularly applicable for shaking table testing where acceleration inputs as an artificial loading can be controlled but the acceleration of gravity cannot. Knee bracing systems are a steel frames designed to absorb the energy imparted by earthquake ground accelerations through the plastic deformations of specially designed and strategically placed knee elements which can be replaced after an earthquake (Bourahla, 1990; Williams *et al*., 2002).

This paper presents the design of a model of ten storey knee braced frame to be subjected to earthquake loading using a shaking table. Before performing the actual testing a numerical investigation of the response of the small scale model and the prototype was carried out to quantify the effect of the similitude distortions.

Design Details of a Ten Storey Small Scale Model

The small scale model is not designed to duplicate a particular structure, but to simulate the behavior of a range of multi-storey frames. Therefore, a typical ten-storey frame of those used in commercial office building is taken as a prototype for the scale model design. The building is a three by three bay ten-storey frame; both interior and exterior spans are 5.40 m and the storey heights 3.60 m (Fig. 1). The prototype structure is made of W305×350 columns and I1406×178 beams. A 1/12 scaling factor ($S_l = 1/12$) is selected for length to fit the building within the headroom of the shaking table. The scaling factor for the elastic modulus is fixed to unity. Since solid round bars are to be used for the main members, the similitude requirements of the dimensional analysis for the cross sectional area and the second moment of inertia (S_l^2, S_l^4) are not satisfied. For this reason, it is not possible to follow the exact requirements of the dimensional analysis. However, some relaxation of the above conditions is possible, provided that the effect is quantified and can be compensated for as will be discussed later.

The model to be tested on the shaking table is designed to resist several earthquakes scaled to give a maximum ground peak acceleration of 1.0 g. The main frame members should remain at all times elastic, only the knee elements would undergo plastic deformations. The diagonal braces should not buckle under compression. The other components such as the beam connectors and the screwed connectors are designed to resist the induced forces.

The columns and beams of the four lower storey of the model are made of 19.1 and 15.9 mm solid round bars. Those of the upper storey are reduced to 15.9 and 12.7 mm respectively. A total of 192 columns (285 mm long) and 288 beams (425 mm long) were made and joined together by specially manufactured block connectors so that the centre line length of the columns and beams coincide with the model storey height and the bay width.

The block connectors shown in Fig. 2 are made of steel cubes, designed to ensure rigid nodes, easy fitting and also to allow different structural configurations for future use. The beams and columns are linked to theses blocks by means of 'Hydrostud™' fittings which determined the minimum dimensions of the cubes. It should be noted here that the size of the block connection is considerable when compared to the frame member lengths (about 20% and 15% of the storey height and bay width respectively) which is common in small scale models. A total of 176 blocks were made in four types, 16 blocks to fix the bottom storey columns on steel plate bases to be clamped to the shaking table platform, 16 intermediate blocks that permit the transition from 19.1 mm diameter columns to 15.9 mm columns, 48 blocks for the lower storey member connection and 96 for the upper storey. The most important features of these connection blocks are that they permit a relatively easy mounting of many building configurations and damaged elements may be easily replaced.

The small scaling makes the manufacture of the bracing system very difficult. However, by designing a relatively gross connection it is possible to achieve the required knee element fixity, the brace pinned connections, the easy replacement of the yielded knee elements, whilst making the whole system removable. A unit bracing system is composed of thirteen pieces. Two knee elements made from solid bars 8 mm in diameter and 105 mm long designed to be clamped to the columns and beams by means of four connectors (Fig. 3).

The knee element strength is controlled by a variable depth groove at ends. Each of the two braces is composed of tension bar (8 mm diameter, 225 mm long) and two screwed connectors, one is left hand threaded, the other is right hand threaded, which enables the tension to be adjusted in the brace elements (Fig. 4). The central beam connector ensures a pinned connection from the beam in such a way that their centre lines coincide at one point in the middle of the beam.

In order to realize the Artificial Mass Simulation (AMS) condition, extra mass is needed at each floor (Fig. 5). To this end 6 mm thick steel plates were used to simulate the building floor and to serve as support for lead masses. In order to minimize alterations to the structural stiffness, the plates were pinned to the edge of the block connections.

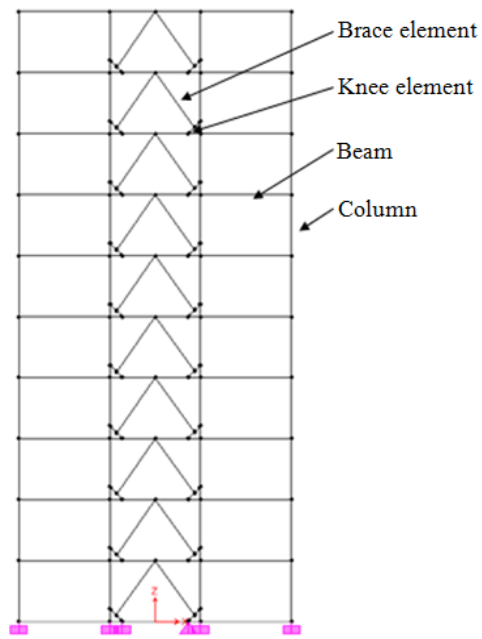

Fig. 1. Ten storey knee braced frame

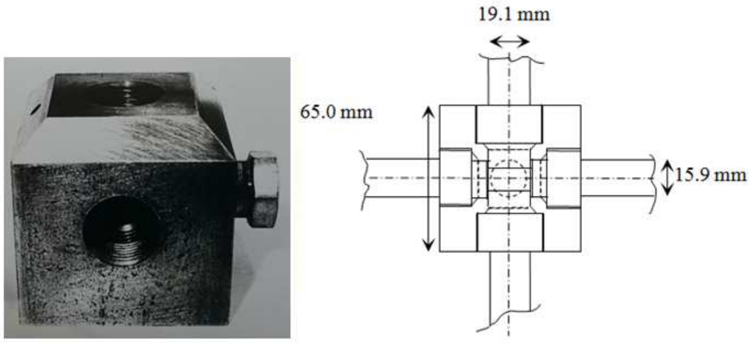

Fig. 2. block connector

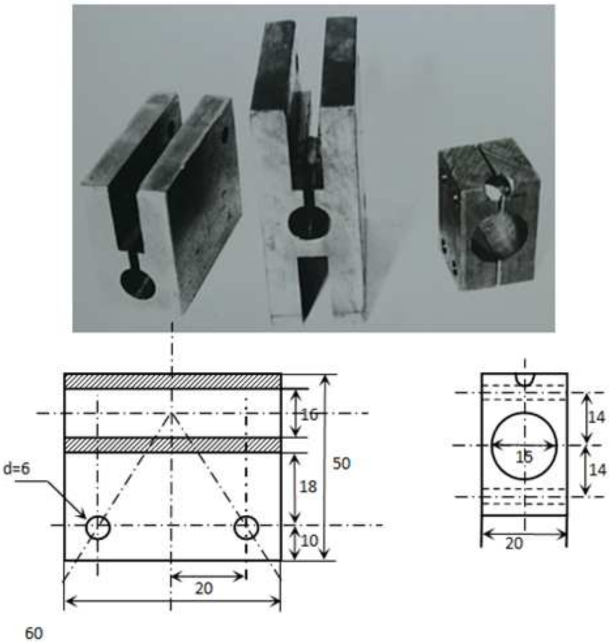

Fig. 3. Brace and knee element connectors

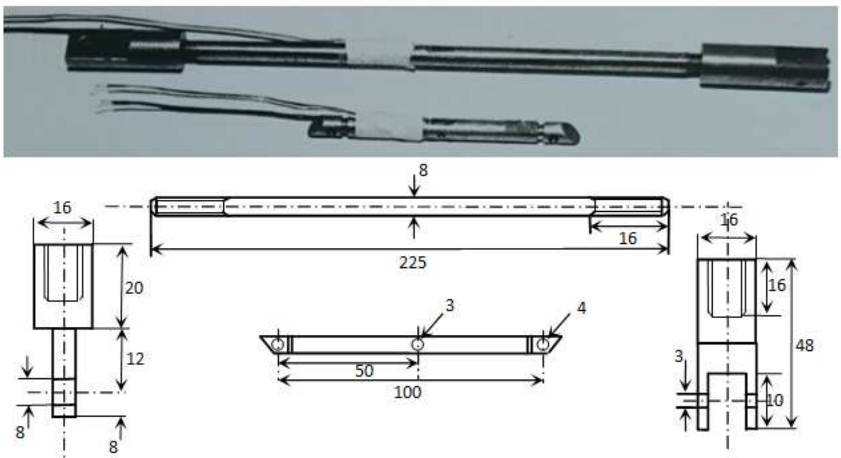

Fig. 4. A brace and knee element

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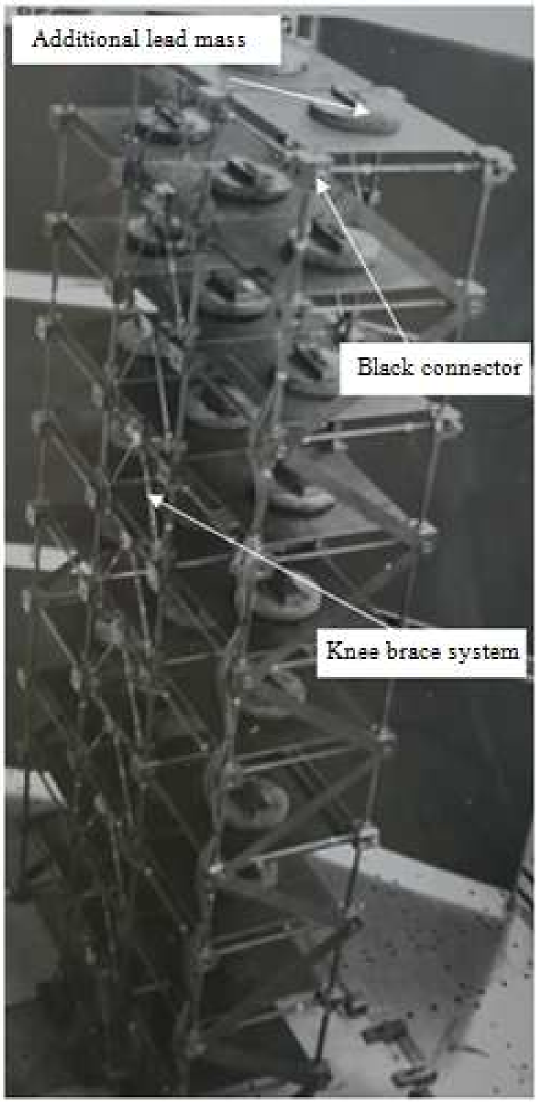


Fig. 5. Overall view of the small scale model

Modified Similitude Requirements

The primary objectives of the model testing are to investigate the dynamic behavior of knee braced steel frames and to get a better understanding of the performance of their energy dissipation mechanisms without being interested in duplicating the exact response of a particular real structure, provided that the response of the model is within the range of similar real buildings. Thus an analytical study is carried out in order to quantify the discrepancies between the scaled model and the prototype structure due to the distortion in the similarity requirements.

The main members (columns and beams) of the knee braced frame are designed to remain elastic at all times for these tests. The only part that is subject to yielding is the knee elements which constitute the main source of damping. Therefore the knee element geometric characteristics were kept under the similarity laws and an attempt to duplicate the overall dynamic properties of the structure is made by using an overall simulation which for a given length scales coefficient S_l requires:

$$\frac{K_p}{M_p} = Sl \frac{K_m}{M_m}$$

Because of the uniform distribution of the stiffness and masses in the structure, K is taken as the equivalent lateral storey initial stiffness of the knee braced frame and M is the floor mass. Subscripts m and p relate to the model and the prototype respectively. The above equation is used to adjust the model masses to satisfy the scale factor.

Analytical Correlation between the Model and the Prototype

The discrepancies in response between the small scale model and the prototype structure are quantified through a comparative numerical study of the modal characteristics and the responses of the two structures to El-Centro N-S component earthquake in the elastic and plastic range. The scaled model and the prototype frequencies are within 10% (Table 1) and the mode shapes are very close (Fig. 6).

The inter-storey drift is an important response parameter in this testing context of the small scale KBF model and should be kept as close as possible to the prototype value. The scaled maximum lateral displacement of the model are plotted together with those of the prototype in Fig. 7. The overall displacements are in good agreement. The maximum error which is less than 10% occurred first at the level of columns dimensions transition and the error sign changes in the upper storey.

The key parameter of testing the KBF small scale model is to assess the energy dissipation capacity of the knee elements and the local ductility to measure the damage that the knee elements may endure under a seismic ground motion. The relevant response parameters are the maximum ductility and the hysteresis loops. As can be seen in Fig. 8 the distribution of the maximum ductility of the knee elements at each storey in the model are higher than those of the prototype but the trend is similar. However, the accumulated plastic rotations of the knee elements are closer except for the 4th transition storey (Fig. 9). It can be stated that the small scale model can portrayed the height distribution of the plastic deformations of the knee elements.

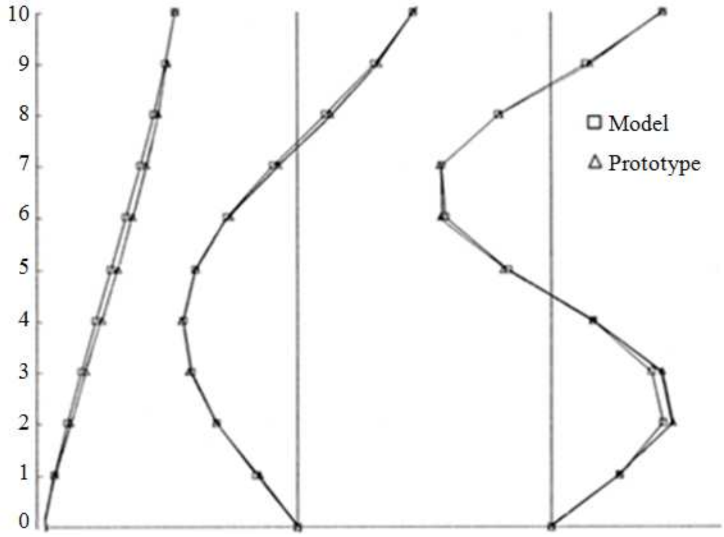


Fig. 6. Model and prototype mode shapes

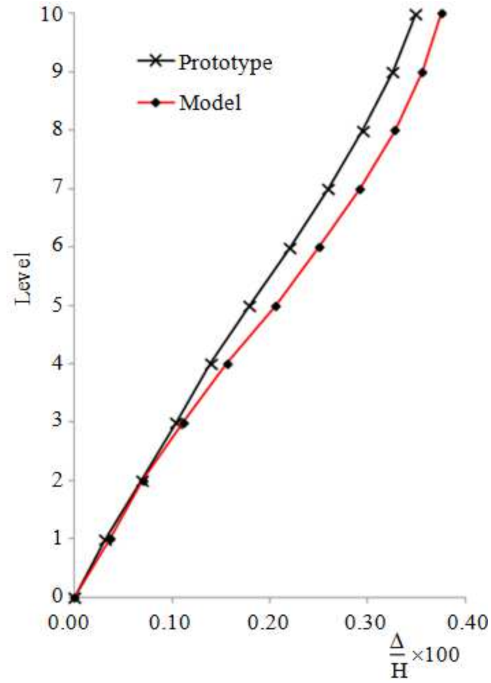


Fig. 7. Maximum lateral displacement

Table 1. Model and prototype natural periods (prototype time)

	Periods (s)		
Mode	Model (T_m)	Model (S_l*T_m)	Prototype
1	0.25	0.87	0.90
2	0.08	0.28	0.28
3	0.05	0.17	0.15

Representative hysteresis loops of knee elements at a lower storey for both the model and the prototype are plotted on Fig. 10. They are slightly different in the way that intermediate moment-rotation hysteresis loops developed in the prototype are wider.

In terms of energies, the plot of the time histories of the input energy, the structural damping energy and the dissipated hysteresis energy show that the scaled model energies are matching those of the prototype (Fig. 11). This is very important because the objective of this small scale modeling is to investigate the capability of the knee bracing system in dissipating the imparted energy.

The time histories of the top floor displacement in Fig. 12 and 13. Show that the prototype and the model oscillations are on phase, but the major peaks of the model are larger in the elastic response. The amplitudes of the vibrations however are comparable in the nonlinear response.

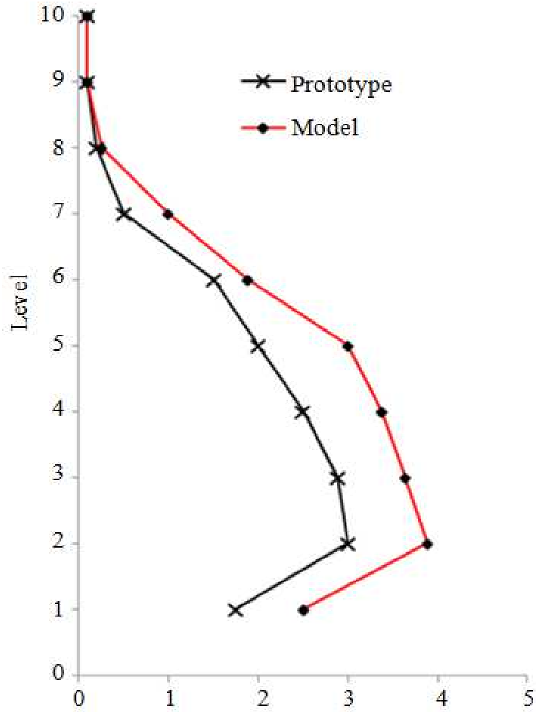


Fig. 8. Maximum storey knee element ductility

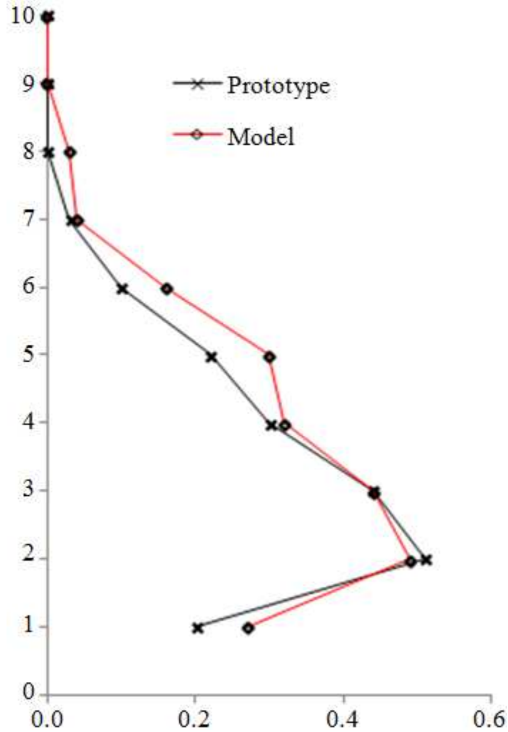
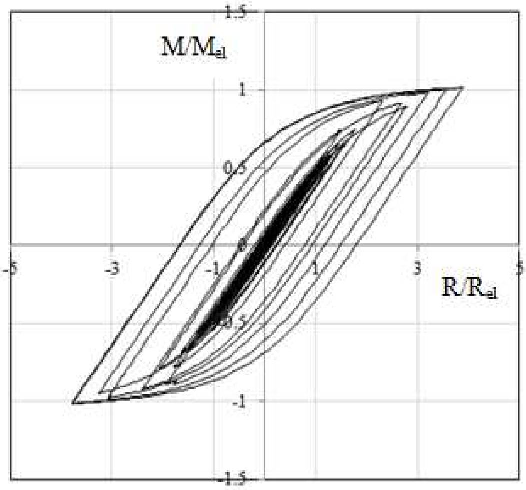
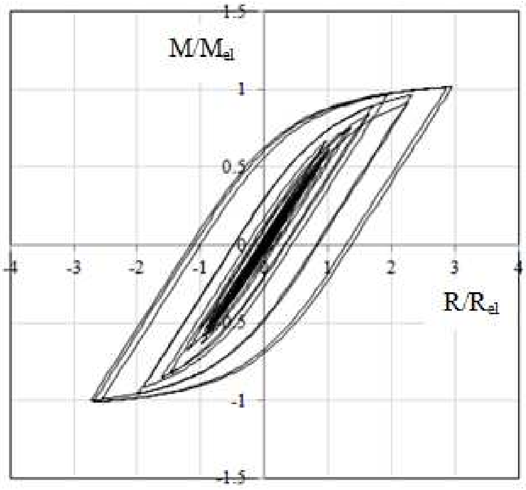


Fig. 9. Storey accumulated plastic rotation of knee element



(a)



(b)

Fig. 10. Moment-rotation hysteresis loops of the knee elements (a) Hysteresis loop of the model (b) Hysteresis loop of the prototype

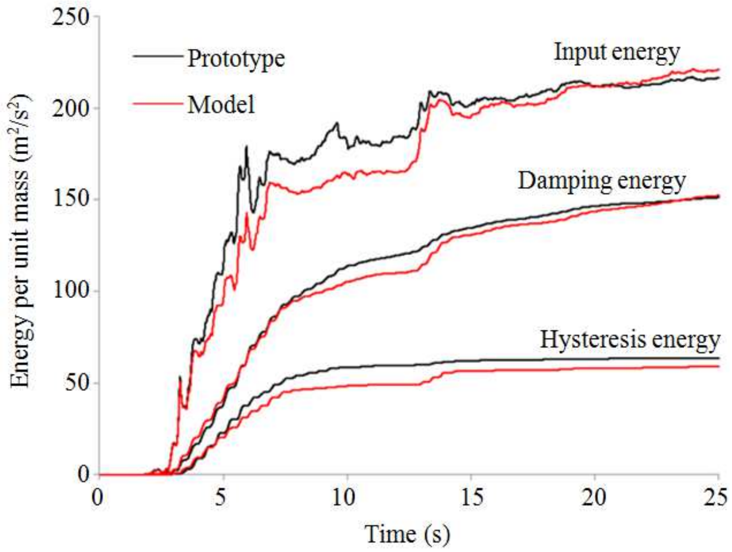


Fig. 11. Energy time histories

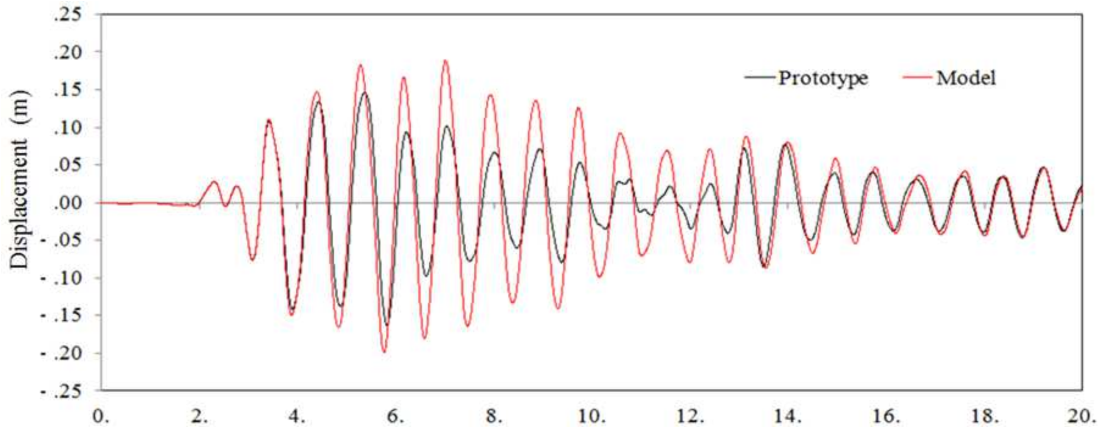


Fig. 12. Linear response of the top floor displacement time histories

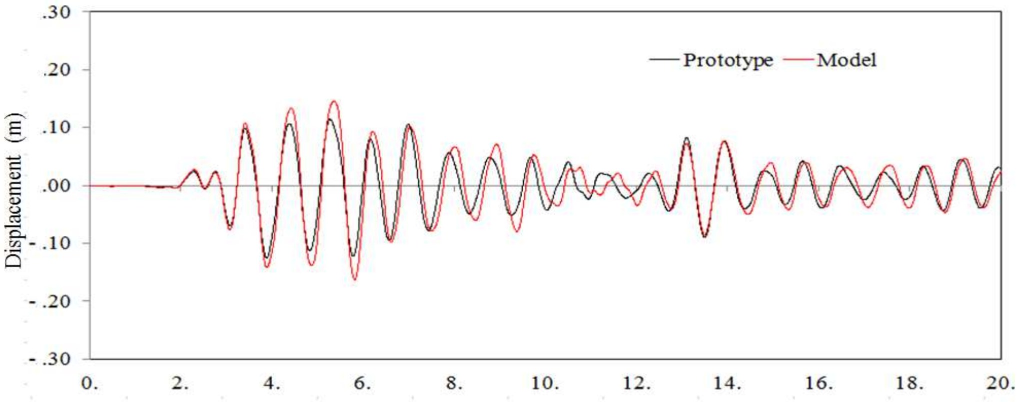


Fig. 13. Nonlinear response of the top floor displacement time histories

Conclusion

The small scale dynamic model has proved to be a powerful tool in investigating and understanding the structural behavior in many complex situations where analytical techniques are inadequate or to validate the existing analytical procedure by developing mathematical models that correlate well with the experimental results. However true replica models are practically impossible to build and test because of the severe restrictions imposed on the model. Alternate scaling laws have been shown to simulate adequately the behavior of the structure and some particular distortions of the similitude requirements can be accounted for.

The artificial mass simulation used in this study was successful in correcting the unsatisfied similitude conditions using an overall mechanical simulation. As demonstrated, the dynamic characteristics as well as the response parameters of primary interest such as lateral deflection, knee bracing ductility and the energy dissipation capacity of the small scale model are within the range of true scale building.

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Author's Contributions

All the authors have participated equally in the research work.

Ethics

This work has not been published elsewhere so there are no ethical issues known to authors that may arise after the publication of this manuscript.

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