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AN INVESTIGATION ON THE DYNAMIC RESPONSE OF THE SHAKING TABLE STEEL DECK USING FINITE ELEMENT

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Abstract. This paper presents the results of an analytical study on the dynamic characteristics of the Shaking Table facilities at Sharif University. This 3 degree of freedom shaking table is driven by 3 servo-control hydraulic actuators, and consists of a 12 ton, $4_m \times 4_m \times 0.6_m$ steel deck. The main objective of this investigation is to identify the degree of flexibility of the deck, and its adverse effects in causing errors in the simulation of seismic effects on different structural specimens. Many frame specimens of different weights and configurations are subjected to seismic motions, and their responses are calculated using FE models. Some of these models were designed to account for eccentric torsion. The results indicate that the deck is generally rigid enough to simulate seismic responses within the defined degree of precision. However, it is shown that there could be some undesirable local flexibility at the base connections that in turn cause additional drift of the frame specimens. A cross shape chassis was designed to overcome this shortcoming. Further study revealed some hidden weaknesses, which were eventually resolved in the final design. It is shown that a noticeable improvement can be obtained in the simulation of seismic response by utilizing this modified chassis.

1 INTRODUCTION

1.1 Objectives of the study

Theoretical and experimental researches in earthquake engineering are mostly verified by tests on shaking tables, which the accuracy of their results is of great importance. These results might be unreliable as it is observed in the last century that the results driven from shaking table tests had errors and deficiencies.

Shaking tables parts are categorized in three main electronic, hydraulic and mechanical sections. The most substantial part of the mechanical section is the Steel Deck, which performs as the earth crust that exerts rotational and translational displacements to the specimen by forces driven from hydraulic actuators. The Steel Deck is connected to the rigid foundation by hold-down struts which allow its translation in all directions except vertical to the foundation.

The shaking table of Sharif University of Technology mechanism is like most of the modern shaking tables which is based on displacement control. In this control system the fundamental assumption is the rigid performance of the steel deck. Based on this assumption the steel deck performs as a rigid body that is utilized to transit seismic load in the form of displacement and rotation, it also supports the specimen as a foundation. In spite of this assumption the actual performance of the steel deck in practice is flexible, which means that strains are developed in steel plates of shaking table's deck that create errors in the results driven from the tests. In this study we track and categorize the errors caused by this malfunction, and by using FE methods the influences of flexibility of the steel deck on the test results are investigated. It is also studied that increasing the rigidity of the steel deck utilizing chassis reduces the effect of strains on accuracy of the test results. These investigations also indicate the hidden weakness of the semi-rigid connection of the specimen to deck which is in contrary to the assumption of rigid connection between columns and steel deck. An innovative cross shape chassis is designed and studied by FE methods to overcome this weakness.

1.2 Overview of SST (Sharif University of Technology shaking table)

3 degree of freedom SST is stimulated by 3 hydraulic actuators in 2 horizontal directions which also has the ability to rotate around vertical axis. Its control system is one-variable controller (OVC) in which displacement is the variable. SST deck is a $4_m \times 4_m \times 0.6_m$ steel box with top, bottom and side 25mm thick plates. Seven 6_{cm} thick joint stiffeners with rigid behavior are located at the end of each of the 3 hydraulic actuators and 4 hold-down struts. 2_{cm} thick stiffeners are designed perpendicular to the rigid joint stiffeners in order to transfer the displacement uniformly and prevent punching of the side and bottom plates. $0.8_m \times 0.8_m$ mesh of vertical 2_{cm} thick stiffeners is designed to increase rigidity of the top and bottom plates of SST. It is expected that this steel deck present a rigid behavior under extreme dynamic loading, but in fact this not totally fulfilled. The details of SST steel deck are illustrated in Figure 1 & Figure 2.

Figure 1: SST shaking table steel deck & horizontal actuateurs

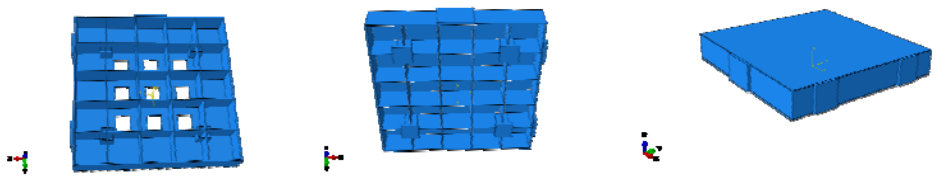

Figure 2: 3D FE model of SST steel deck

2 TRACKING AND CATEGORIZING THE ERRORS

In order to tracking the errors revealed in test results due to imperfect rigid behaviour of the steel deck, these errors should be categorized in 2 main branches. First, strains created in side plates because of extreme dynamic forces driven by hydraulic actuators. As seismic loads are transmitted to the steel deck through displacing these side plates by hydraulic actuators, these strains result in inaccuracy of desirable displacement with that exerted to the specimen in experiment. This problem is solved using Feedback Control System, which compensates for these undesirable displacements. Second, strains created on top and bottom plates. Bottom plate strains are located adjacent to hold-down struts joint stiffeners. Due to the usage of stiffeners in these areas, these strains are negligible, but the strains created on top plate of the steel deck are noticeable and Feedback Control System is not capable of compensating for these undesirable displacements. These undesirable displacements on top plate of steel deck are divided into two main branches. The first one is the translational displacement which occurs in 3 directions in which the vertical displacement has the most influence on the test results that causes some additional drift of the frame specimen (Figure 3), but the other two horizontal displacements are negligible. The second one is the rotation of the top plate which is also negligible.[1]

FE models consisting of SST steel deck and different types of steel frames under various types of loading were developed to investigate the errors caused by undesirable vertical displacements mentioned.

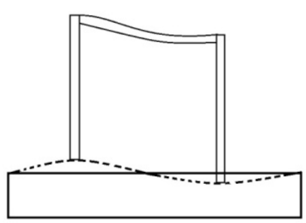

Figure 3: Schematic vertical displacements in top plate of SST steel deck

3 INTRODUCTION TO FE MODELS OF SST STEEL DECK AND FRAMES UNDER VARIOUS LOADINGS

3.1 FE modeling of SST steel deck box and steel frame specimen

A 3D nonlinear FE model of SST steel deck, shown in Fig. 2 is generated. The technique of FE analysis lies in the development of a satisfactory mesh arrangement which leads to insignificant errors; therefore, at the beginning of this study a number of different trial models were created. For this reason different models with solid elements[1] were created and the results were checked. Taking into account the fact that mesh generation should balance the size and type of mesh elements and reasonable analysis time, it was concluded that solid element type could not fulfill these expectations, so shell element type was utilized for modeling. Shell behavior of model parts due to one negligible dimension of them in comparison to two dimensions is logical and presented reasonable results with an acceptable accuracy. Also fine mesh was used in high stress areas and coarser mesh for other areas.[2]

In this research a symmetric steel frame was modeled as a specimen. This frame was consisted of 4 columns and 4 beams, 2_m high with 1.6_m span width with square shaped $0.15_m \times 0.15_m$ columns and rectangular shaped $0.14_m \times 0.07_m$ beams. The span width is designed in a way that column bases would not be located on top of the intersection of any of the steel deck vertical stiffeners.

The interaction between frame column bases and top plate of the steel deck was tied as surface-to-surface. Other parts of frame and the steel deck were merged to each other to simulate welding condition. Material over-closure was prohibited since separation of surfaces was permitted. The iteration procedure is based on full Newton–Raphson iteration method, an iterative process of solving the nonlinear equations, which is performed within each increment to achieve a quadratic convergence.

The stress–strain relationship for structural steel elements were modeled by means of a quadrilinear relationship depicted in Fig. 3. For the elastic part of the stress–strain curve, the values of Young's modulus and Poisson's ratio of the steel are considered 206 GPa and 0.3, respectively. The tangential stiffness beyond the yield point for steel sections is defined as 2% of the initial modulus of elasticity up to $11\varepsilon_y$ followed by its related ultimate stress at $120\varepsilon_y$ (see Fig. 4).[3]

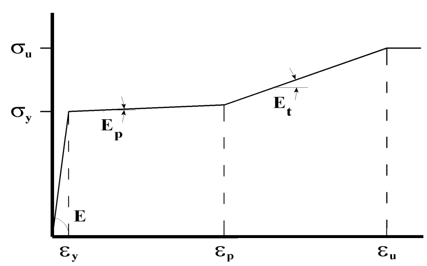

Figure 4: Idealized material behaviuor used in FEM analysis

3.2 Loading pattern on frame and steel deck

45 ton dead load is exerted on the steel frame beams in symmetric and asymmetric patterns. A pressure of 10 kg/cm^2 magnitude was applied on each beam upper surface as a symmetric loading pattern, and a pressure of 20 kg/cm^2 magnitude was applied on half of the

[1] 3D element in nonlinear FE modeling

beams upper surface as an asymmetric loading pattern (Fig. 5).

Manjil earthquake recorded at *Abbar* station was utilized as the dynamic loading exerted to the SST steel deck through side stiffeners located at the end of hydraulic actuators. Whole recorded time of *Manjil* earthquake is more than 30 seconds, but in order to reduce the analysis time reasonably, a 3 second period of its peak displacements was selected to be applied. There are also series of specimen which have brace in one of their span (Fig. 5) to provide the asymmetric stiffness.

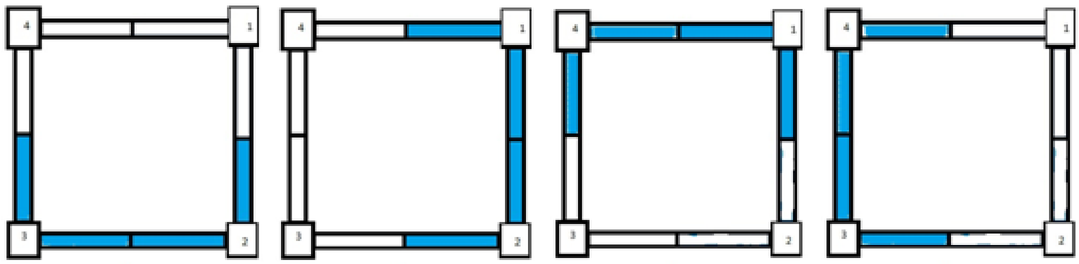

Figure 5: Upper view of asymmetric dead loading patterns 5.a to 5.d (left to right). The braced frame are indicated.

3.3 Frame with symmetric stiffness under symmetric dead loading

Steel frame specimen and steel deck tied to each other without neither base plate nor chassis were modelled. The results indicate that punching occurred on the top plate of the steel deck beneath column bases which should be prevented by using base plates.

As it was predicted, by exploiting $0.3_m \times 0.3_m \times 0.04_m$ base plates beneath each column, punching vanished, but displacements were in a range that developed effective errors on the results (Fig. 6 & Fig. 7). Fig.6 illustrates the displacement beneath each column base plate, and Fig 7 indicates the absolute difference between each of two columns connected by a beam.

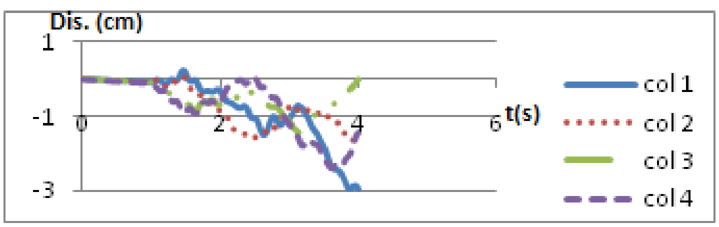

Figure 6: Displacement-time diagram beneath each column base plate

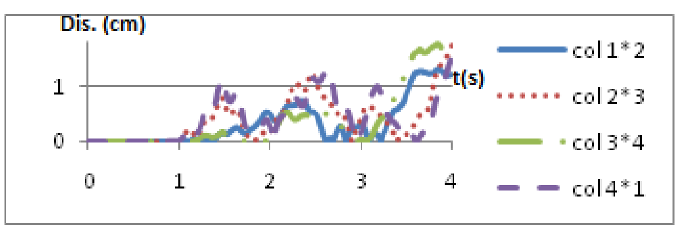

Figure 7: Absolute displacement difference between each two columns connected by a beam

According to the obtained results, the errors are not negligible, so utilizing chassis beneath column bases is inevitable. Displacements beneath column bases with chassis under various types of loading are studied.

Therefore IPB 300 profile with 2 stiffeners perpendicular to it on each side was used as an H-shape chassis. These 4 stiffeners were utilized to resist against rotation around weak axis of the chassis (this is a standard chassis which is usually utilized in shaking table tests). The length of the chassis should be at least 1_m in order to be more than the distance between two adjacent interior vertical stiffeners in the SST steel deck. Displacement and stress contours of the SST steel deck and frame specimen with mentioned specifications and loading pattern is presented in Fig. 8. Diagrams illustrated in Fig. 9 indicate that the displacement beneath column bases was reduced to a range which results in negligible errors in test results. In this case, SST steel deck performance is reliable (based on the studies the absolute difference less than 0.01_m causes negligible errors in test results of this specific frame specimen).

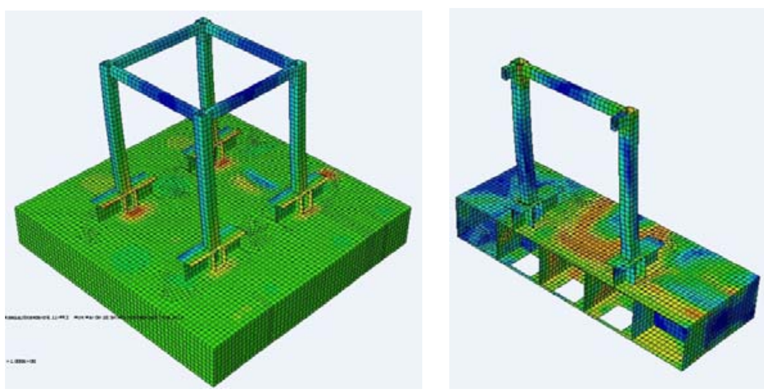

Figure 8: Strain contour (left), Stress contour (right)

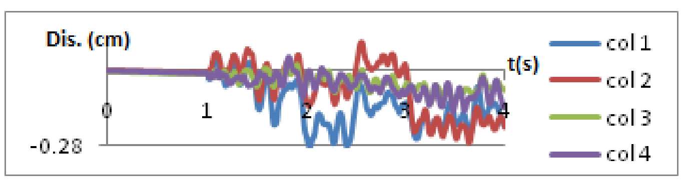

Figure 9: Displacement-time diagram beneath each column base plate

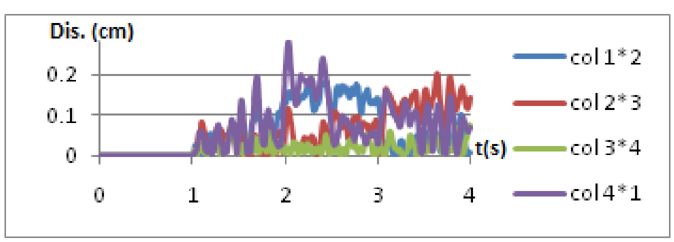

Figure 10: Absolute displacement difference between each two columns connected by a beam

3.4 Frame with symmetric stiffness under asymmetric dead loading

In this section the same frame specimen is investigated under loading pattern of Fig. 5.d which is the most critical condition that results in the largest errors. This model presents the influence of asymmetric dead loading which causes additional absolute differences between column bases displacement that increase the errors. This loading pattern causes unavoidable torsion forces in the frame specimen which intensify the errors. Therefore the influence of torsional forces is also observed in Fig. 11 to Fig. 13. The results indicate that SST steel deck performance is still reliable.

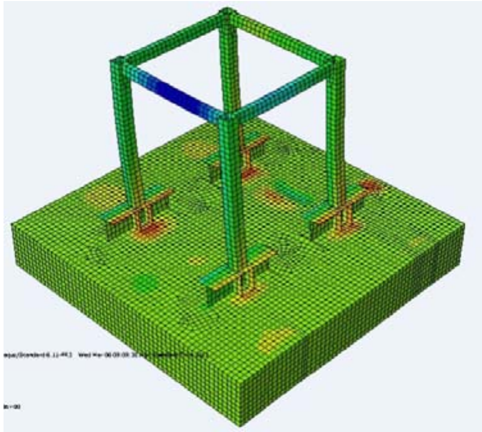

Figure 11: Strain contour

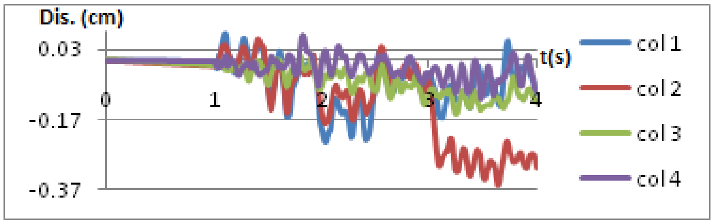

Figure 12: Displacement-time diagram beneath each column base plate

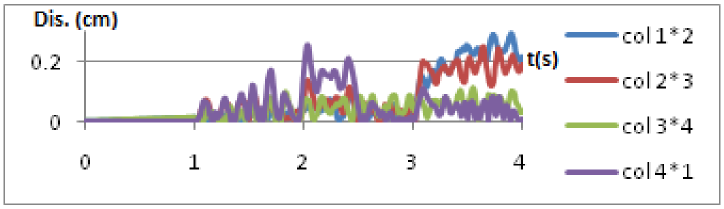

Figure 13: Absolute displacement difference between each two columns connected by a beam

3.5 Frame with asymmetric stiffness under symmetric dead loading

The flexible behaviour of SST steel deck with a braced frame specimen is investigated in this section. Two U60 profiles were used as braces connected to the frame by $25_{cm}\times25_{cm}\times1_{cm}$ gusset plate in order to modify the frame symmetric stiffness. The frame specimen was modelled with braces inserted in each of the four spans, and the most critical condition is presented in this section (Fig. 14). In this way major forces are exerted to the 2 braced column bases, therefore absolute differences in column base displacements are intensified. Asymmetric frame stiffness causes torsional forces in the frame specimen which is greater in comparison to the frame specimen of section 3.4. In spite of these additional forces which result in increasing the absolute differences in column base displacements, the results are still reliable. It is noticeable that Fig. 14 illustrates the extreme effect of asymmetric stiffness of frame without chassis which is not reliable, but chassis frame was also analyzed and Fig. 15 & Fig. 16 indicate the results of chassis frame analysis which can be reliable. A noticeable point in this study is the uplift of one of the braced columns which caused greater absolute difference in column bases displacements (Fig. 16).

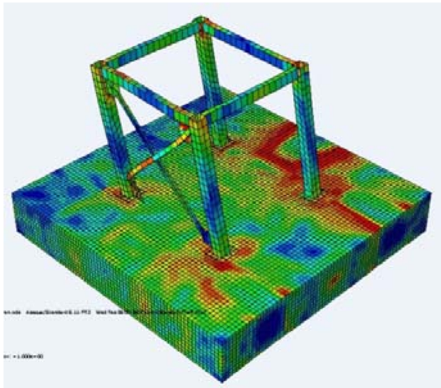

Figure 14: Stress contour for frame without chassis

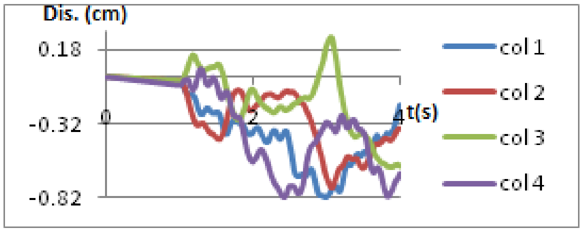

Figure 15: Displacement-time diagram beneath each column base plate for frame with chassis

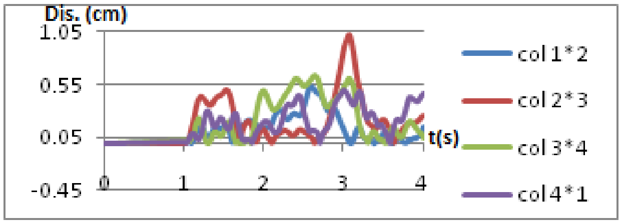

Figure 16: Absolute displacement difference between each two columns connected by a beam

3.5 Frame with asymmetric stiffness under asymmetric dead loading

Eventually, the most critical condition for the frame with braces under asymmetric dead loading pattern was investigated. Results indicate the reliable performance of SST steel deck. In spite of increasing column base displacements, they are still in an acceptable range, which cause errors less than 2% of moments and forces in the frame specimen.

4 INVESTIGATION OF CHASSIS ROTATION AROUND WEAK AXIS AND INTRODUCING AN INNOVATIVE CROSS SHAPE CHASSIS (CSC)

According to the investigations presented in this paper, it was verified that by utilizing base plate and chassis the rigid behavior of SST steel deck is satisfactory. Frame specimen earthquake simulations experiments on shaking tables are based on the assumption of rigid connection of the frame columns to the steel deck as a foundation. By utilizing chassis the rigid behavior of the steel deck is satisfied, but it diminishes the rigid behavior of the connection to the steel deck. In fact, rotation of the chassis around its weak axis, turn the rigid into semi-rigid connection (Fig. 17). To solve this problem, an innovative CSC is introduced and investigated in the same conditions. CSC is consisted of two intersecting IPB300 profiles with the length of more than 1_m for each of them (Fig. 19). CSC performs as a rigid connection between the frame specimen and the steel deck (Fig. 18). Not only CSC enhances the rigid connection performance, but also increases the rigidity of the SST steel deck which is of great importance.

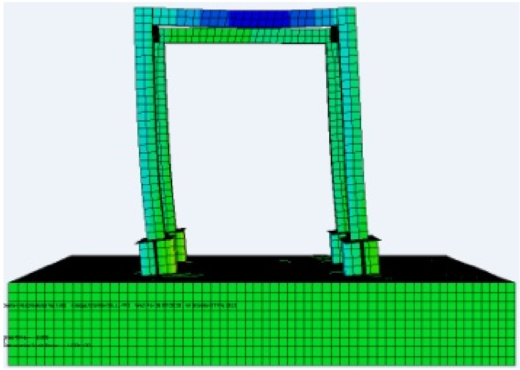

Figure 17: Side view of frame and deck during analysis with simple chassis

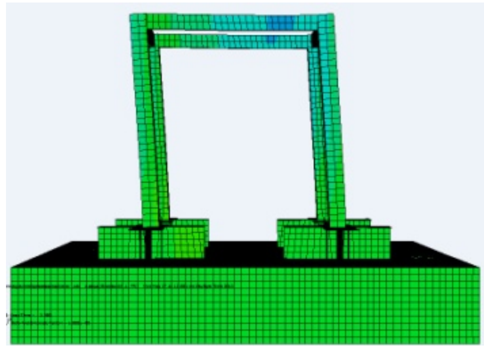

Figure 18: Side view of frame and deck during analysis with modified CSC

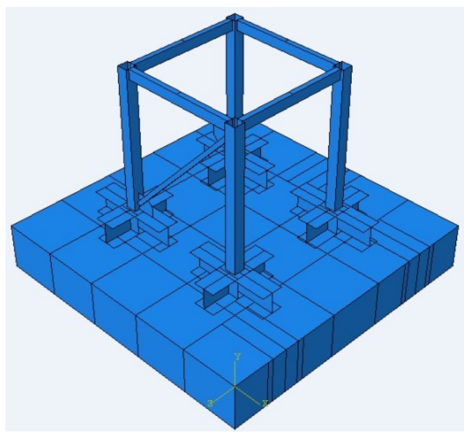

Figure 19: View of final frame and steel deck with CSC of SST

5 CONCLUSION

Investigations in this paper indicated that SST steel deck rigid behavior is in a reliable range. But in the case of experiments with full dead load capacity of SST and extreme dynamic loading the utilization of chassis is necessary in order to enhance the rigidity of SST steel deck to increase the accuracy of the test results.

In the case of using chassis as a connection between frame specimen and SST steel deck, the rotation of the chassis around its weak axis is observed which reduces the rigidity of the connection and turning it into semi-rigid connection that causes errors in the test results. To solve this problem, CSC is introduced and investigated which provides desirable performance by increasing the rigidity in both steel deck and chassis connection.

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