Effects of Soil-Structure Interaction on the Seismic Response of Base Isolated in High-Rise Buildings

Farzad Hatami
Amirkabir University of Technology (AUT), Tehran, Iran
Email: hatami@aut.ac.ir

Hamed Nademi
Islamic Azad University of Yazd, Yazd, Iran

Mohammad Rahaie
Sharif University of Technology (SUT), Tehran, Iran

***Abstract*—In this paper, a real 10-story base isolated structure, designed according to IBC, 2009 guidelines, is selected as a case study. A semi-infinite cone model has been used to evaluate base soil characteristics of buildings embedded in layered flexible half space. Three different soil types are selected according to soil classifications in the code. The analysis has been performed using Loma Prieta and Northridge's time history earthquakes considering the Soil-Structure Interaction (SSI) effects or base isolated system. The comparison of natural period, base shear and total relative displacements of the structure has been realized based on analytical models. Numerical results show that Soil-Structure Interaction has negligible effects on the base shear ratios of this type of buildings on very stiff soil. Also, damped periods of base isolated buildings resting on the soft soils, have been increased regardless of the height of the building or shear-wave velocity.**

***Index Terms*—soil-structure interaction, cone model theory, base isolation, LRB, numerical model**

I. Introduction

Base isolation systems are widely used in high-rise buildings with the aims of reducing their seismic vulnerability against natural hazards. In this regard, Soil-Structure Interaction has a significant effect on seismic responses of structures and had not been taken seriously until San Fernando earthquake in 1971. This context intends to investigate the effects of SSI on the response of base isolated high-rise buildings founded on an elastic soil layer overlying rigid bedrock and subjected to harmonic ground motions.

Several investigations by Skinner have been done to develop new methods of seismic resistant design in New Zealand which resulted in presenting the new isolation concept of the laminated rubber bearing [1]. Robinson's experiments demonstrate that displacements of isolation systems should be reduced by adding more damping mechanisms to the structure besides the LRB damping [2]. The main use of the lead core of the LRB is to damp additional strain of the entire structure. Kelly, Buckle and Mayes made an extensive report on the history, applications and performances of several damping mechanisms which had been developed till 1990 [3], [4]. Tsai and Kelly's study represent that for a base-isolated shear building, damping within the lead core of the LRB causes an increase in the accelerations of lumped masses [5]. Also, the rubber bearing increases the global flexibility and restoring force which leads to lowering accelerations and inertial forces in the structure [6]. An experimental and analytical research was conducted on the base isolated structure assuming to be a SDOF system [7]. Iemura and Pradono observed that damping plays an important role in the bearing stiffness for various bridge retrofit strategies [8]. Abe *et al*. proposed two kinds of mathematical models for laminated rubber bearings under multi-axial loading. Then they conducted tri-axial hybrid experiment in which two-directional displacement paths are given to the bearings under a constant vertical load to see whether the models accurately predict responses or not [9]. The effects of SSI and isolation on the bridges with elastomeric bearings have been reported by Tongaonkar and Jangid in 2003 [10]. They show that considering SSI could lead to more precise results of displacements at abutments. Dicleri *et al*. determined that SSI should be considered in isolated bridges, regardless to the soil stiffness. It is acquired by assuming a non-deteriorating force-deformation relation which entirely explains the natural nonlinear behavior of investigated isolators [11]. Base isolators which indicate a hardening behavior to resist an increasing load have been developed for buildings with utmost four stories subjected to moderate earthquakes by Pocanschi and

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Phocas [12]. In a noteworthy practice, Spyrakos implemented an equivalent two-degree-of-freedom system for a base isolated multistory building, which showed that dynamic characteristics of this type of structures, including frequencies, damping and mode shapes can be modified significantly by considering SSI effects [13]. Using nonlinear dynamic analysis which includes soil-structure interaction and footing base uplift, Anastasopoulos *et al*. and Abdel Raheem have shown that Hysteric damping of the base soil can cause isolating effects especially on shallow foundations [14], [15]. Wang *et al*. studied the Influence of SSI on the isolation efficiency of a typical steel girder bridge. Results reveal that while SSI decreases isolation effectiveness, failure of the system for all values of soil stiffness is less probable as the system becomes more isolated [16]. Another experimental estimation was carried out by Zhuang *et al*. in 2014. According to their four shaking table tests, damping ratios which are obtained for the structural models including SSI Effect, are larger for those on rigid foundation. Also it can be seen that by increasing the PGA of excitations, the supposed acceleration magnification factor has been increasing along the height of models [17].

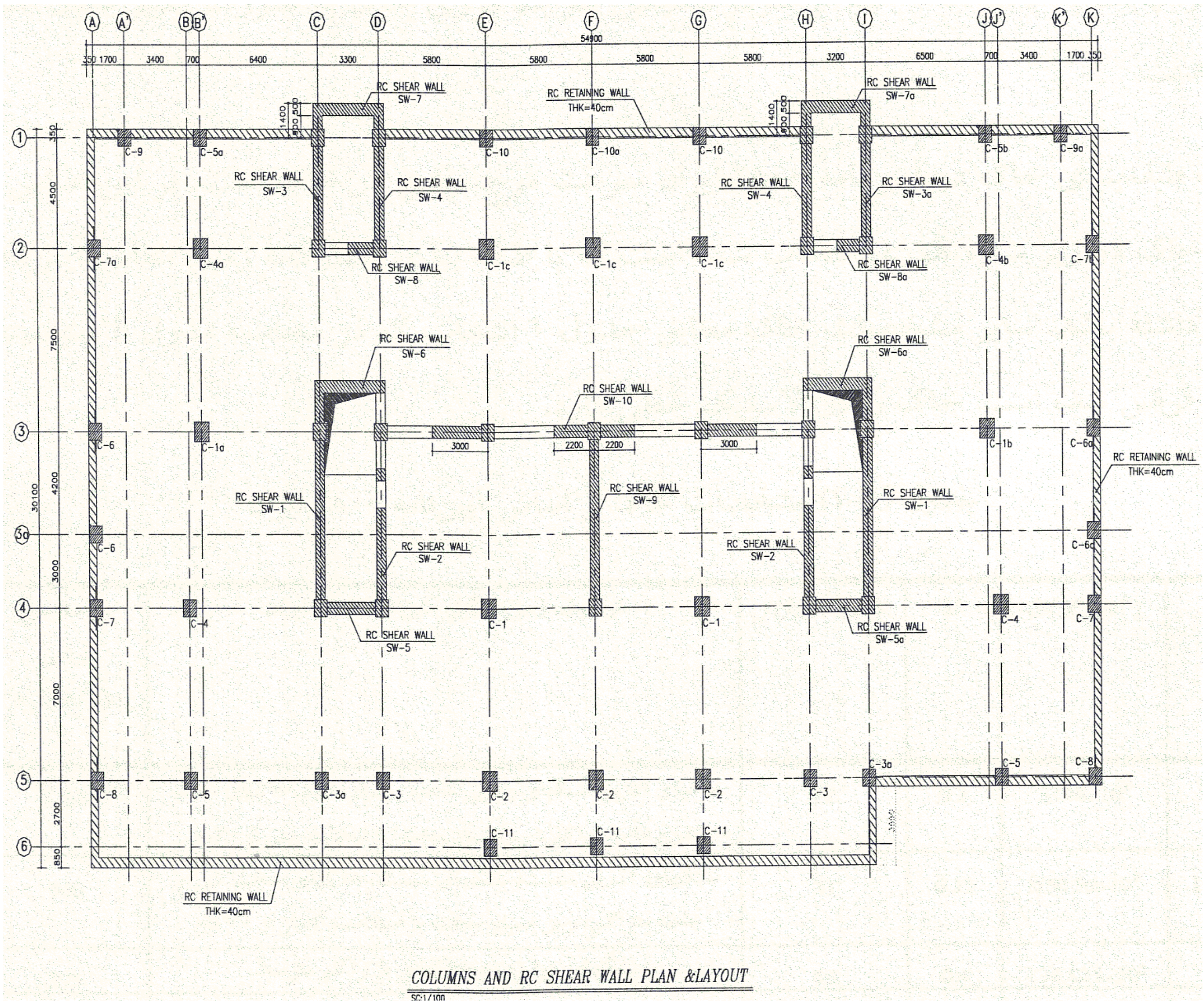

Figure 1. Plane view of the structure

II. Numerical Model of Building

To study the effect of SSI on the seismic response of base isolated high-rise structures, an extensive investigation was undertaken. A real 10-story base isolated building with Intermediate moment frames system of reinforced concrete is selected as a case study. It is considered with 11 spans in the longitudinal direction and 6 spans in the transverse direction. Sections of the beams are $300 \times 450mm^2$, sections of the columns are $500 \times 500mm^2$ and the floor height is 3.2 m with solid slabs 200mm thick. The effective weight of each story is taken uniform and equal to 2000 kN. According to ASCE/SEI 7-10 [18], dead and live loads are assumed 6500 N/m^2 and 2000 N/m^2, respectively. Plane view of this building is shown on Fig. 1. The base isolated building is modeled as a shear type mounted on isolation systems with two lateral degrees of freedom at each floor.

For the present study, an idealized mathematical model is considered for simulation of the base isolated structure and soil system. The FE model required for observing in the analysis is shown in Fig. 2. As Fig. 2 shows, soil depth has been considered 50m and length between the center of mass and the end of the model is 180m. Roller and hinged supports have been considered for horizontal and vertical directions along the soil boundaries, respectively. The following assumptions are made for the structural system during modeling: The superstructure elements are assumed with P-Delta effect included. During the earthquake excitation, the superstructure is considered to remain within the elastic limit. This assumption is valid in the presence of the isolator which reduces response of the structure considerably. The floors are assumed to be rigid in their planes and the masses are supposed to be lumped at each floor level. The columns are inextensible and weightless, and provide the lateral stiffness. The structure and the soil are in contact on the surface of structural base. As the structural base is much stiffer than the soil, the base-to-soil contact problem is assumed to be rigid-to-flexible contact. These numerical simulations were run using SAP2000 nonlinear software, which is produced by the firm Computers and Structures, University of Berkley, USA.

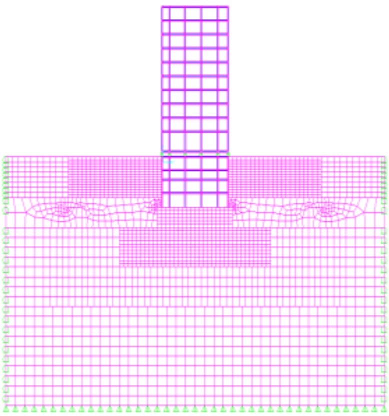

Figure 2. Finite element model of soil-structure Interaction for 2D view of building frame

A. Ground Motions

The system is subjected to two horizontal components of the earthquake ground motion. Nonlinear analytical techniques assuming isolators to be rigid in vertical direction and do not offer any torsional resistance were used for dynamic analysis of structural models [19]. Two records of near-field ground motions considered as seismic excitations in this study are:

- Component of Capitola Loma Prieta Earthquake (1989),
- Component of Sylmar – Olive View Med Northridge Earthquake (1994), With Peak Ground Acceleration (PGA) 0.529 g, 0.823 g respectively. Also the frequency analysis of these accelerograms showed the major distribution of frequency ranges as 0.5 to 1.65Hz and 0.35 to 3.5Hz respectively.

III. Mathematical Modeling of LRB System

The elastomeric LRB isolation system is similar to the laminated rubber bearing with a central hole into which the lead core is press-fitted. The core of lead is used to provide additional energy dissipation which significantly reduces lateral displacements. Therefore, the system becomes essentially a damper hysteresis device. Fig. 3 defines the Bilinear Hysteretic model for the LRB isolator. It should be noted that the natural rubber used for production of the bearings had to be a high damping rubber with an average effective damping of β_{eff} =0.10. The effective stiffness of an isolator, K_{eff}, is calculated for each loading cycle by using the following formula:

$$K_{eff} = \frac{F^{+}-F^{-}}{\Delta^{+}-\Delta^{-}} \tag{1}$$

where F^{+} and F^{-} are the positive and negative forces at Δ^{+} and Δ^{-} which are positive and negative diplacements, respectively. The total effective stiffness of the bearings was also computed on the basis of the assumed main period of the structure.

$$K_{eff} = M\left(\frac{2\pi}{T_1}\right)^2 \tag{2}$$

where, M is the weight of the superstructure, T_1 is the main period of the base isolated structure. The behavior of the bearings was modeled by using a bilinear model which is defined by three main parameters namely;(i) initial elastic stiffness, K_1 (ii) post-elastic stiffness, K_2 and (iii) yield force, F_Y.

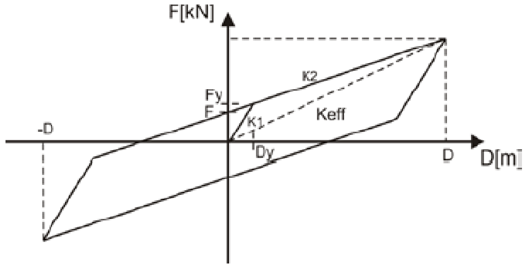

Figure 3. Mathematical model of LRB

The force-displacement diagram of the LRB has been assumed bilinear because it can be applied to all isolation systems used in this practice. Yield force of the lead plug, Q is relevant to the design displacement of bearings and friction coefficient of sliding surface of the isolation system. Also, it is generally designed in such a way to provide the specific value for the isolation period. The following equation is used to determine the relation between elastic and post-elastic stiffness of the rubber:

$$\frac{k_1}{k_2} = \frac{E(1+2\kappa S^2)}{G} \geq 400 \tag{3}$$

where k_1 is elastic stiffness, k_2 is post-elastic stiffness or hardening stiffness,E is modulus of elasticity, κ is correction factor,G is shear modulus and S is shape factor.

IV. Soil Parameters

The base soil behavior is modeled using half-space cone model theory in order to incorporate "SSI" effects into the seismic analysis of the base isolated buildings and also determine the equivalent soil stiffness and damping ratios in the horizontal and rotational directions. Three different soil types of the site (Sc, SD, and SE) are chosen according to IBC, 2009 [20] as shown in Table I.

TABLE I. CHARACTERISTICS OF DIFFERENT SOIL TYPES [20]

Shear Velocity, *Vs* m/s	Shear Modulus, G N/mm^2	K_h N/mm	C_h N.s/mm	K_r N.mm/rad	C_r N.mm.s/rad	Soil Type
70	6.62	2.69E+05	2.49E+04	1.60E+13	3.88E+11	S_E
100	13.50	5.48E+05	3.56E+04	3.27E+13	5.54E+11	S_E
200	54.00	2.19E+05	7.12E+04	1.31E+14	1.11E+12	S_D
400	216.00	8.77E+05	1.42E+05	5.42E+14	2.22E+12	S_C

In Table II, as also shown in the analytical model of Fig. 4, K_h, K_r are horizontal and rotational stiffness and C_h, C_r are cohesive coefficients in the horizontal and rotational directions respectively. In order to consider SSI effects in the analysis, the following dimensionless parameter is defined

$$a_0 = \frac{h_{eff}.\omega_{sb}}{V_s} = \frac{0.55H.\omega_{sb}}{V_s} \quad (4)$$

where, a_0 denotes a stiffness ratio of the base-isolated structure to base soil. h_{eff} and ω_{sb} are effective height and circular frequency of first mode of the isolated structure respectively. Also V_s is the shear wave velocity. This ratio is assumed to be 0 for the fixed base models and approximates to 2 for flexible foundations. In the following table, a_0 values are computed for several multi-story buildings with damped period equal to 2 sec. As the soil stiffness increases, SSI effects on the system become negligible due to decrement of a_0. Additionally, for an unchanged base soil, as the height or weight of the structure increases, a_0 values become more considerable.

TABLE II. a_0 VALUES FOR MULTI-STORY BUILDINGS

Shear Velocity, *Vs* m/s	2-Story	4-Story	7-Story	10-Story
70	0.16	0.33	0.57	0.81
100	0.11	0.23	0.40	0.57
200	0.06	0.11	0.20	0.29
400	0.03	0.06	0.10	0.14

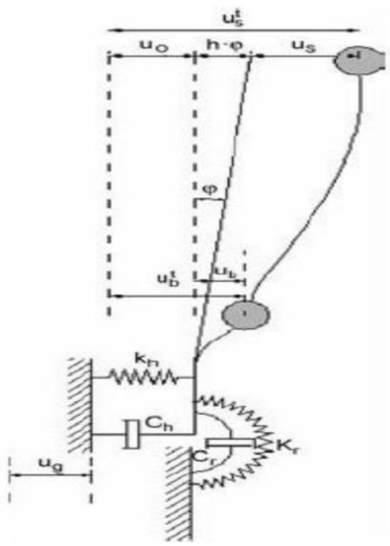

Figure 4. Analytical model of soil-structure interaction

V. RESULTS AND DISCUSSIONS

The effects of SSI on the seismic responses of the base isolated buildings have been evaluated by nonlinear time-history analysis according to IBC, 2009. As previously mentioned, experimental conditions were defined as fixed base isolated model and flexible base isolated model involving base soil properties.

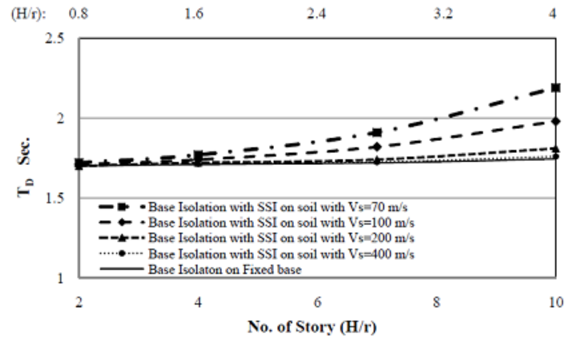

Figure 5. Damped period of isolation system considering SSI effects (Fixed base Td=1.6s)

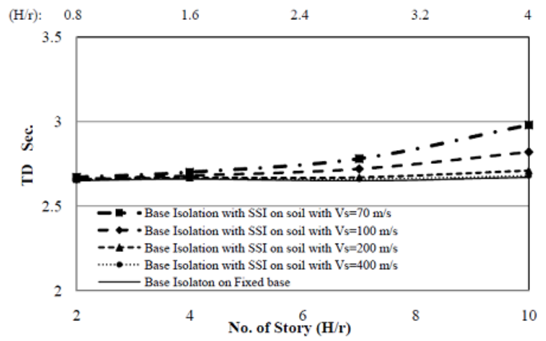

Figure 6. Damped period of isolation system considering SSI effects (Fixed base Td=2.5s)

A. *SSI Effects on the Damped Period of Vibration*

Fig. 5 and Fig. 6 show the changes of damped period of the isolated structures which are on the various types of base soil in terms of number of stories. In each graph, periods obtained from dynamic analysis are greater than initial damped period of structures with fixed base. In buildings with high stiffness and consequently low damped period when performing fixed base analysis, SSI affects damped period of structures significantly. As shown in Fig. 5, for a 10-story building on the base soil with shear wave velocity of 70 m/s, damped period of structure with isolated system has grown 26 percent due to SSI effects while this amount is just 12 percent for the corresponding 10-story building of Fig. 6. Also, it can be observed that by adding SSI terms to the dynamic analysis of the base-isolated structure with different heights and base soil types, damped periods of these structures have been increasing in all cases, especially in high-rise slender structures which are embedded on the soft soils. On the other hand, when twisting happens in the structure, changing $\frac{H}{r}$ can increase the effect of considering SSI on the response of the structure. Note that r is the smaller dimension of the plane of the structure.

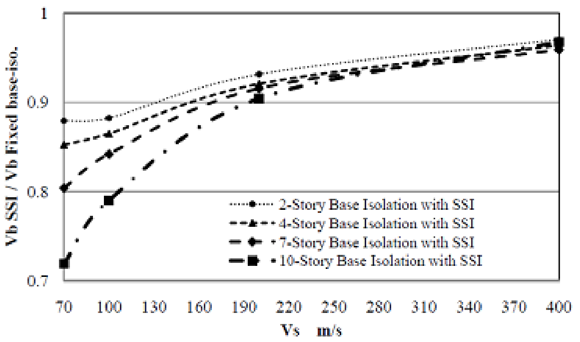

Figure 7. Ratio of base shear considering SSI effects to base shear without considering SSI effects (Fixed base Td=1.6s)

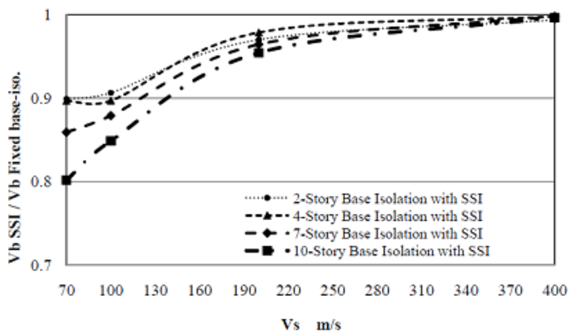

Figure 8. Ratio of base shear considering SSI effects to base shear without considering SSI effects (Fixed base Td=2.5s)

B. SSI Effects on the Base Shear

Base shear values of base isolated buildings with consideration of SSI effects relative to the base shear of the same buildings without considering SSI effects are observed in this part. Fig. 7 and Fig. 8 show defined ratio in terms of shear wave velocity of the base soil for the structures with damped period of 1.6s and 2.5s respectively. Moreover, heights of the structures are another concern of these figures. As shown in Fig. 7 and Fig. 8, base shears of the structures have been reduced due to SSI effects especially for the structures which are on the soft soil ($V_s < 200\,m/s$). The reductions in the base shear ratios change between 10 percent for low-rise structures on the soft soils to 28 percent for high-rise structures on the same soft soil. Also, it takes values below 10 percent for those on the stiff soils ($200\,m/s < V_s < 375\,m/s$) and below 5 percent for those on the most stiff soils ($V_s > 375\,m/s$). As the shear wave velocity increases, the reduction of base shear ratios gradually meet each other for various heights of the structures such that these ratios does not vary by considering low-rise or high-rise buildings which laid upon very stiff soil. Further results indicate that by using the same type of base soils, decrement of base shear ratios for the structures with low damped period is less than the one with high damped period.

C. SSI Effects on Total Displacement of the Structure

The ratio of design target displacement of the base isolator with considering SSI effects to the total displacement of base isolator without considering these effects is illustrated for the real 10-story structure with damped period of vibration of 2 sec in Fig. 9. As shown in this figure, if SSI effects was included in the model, it reduces the amount of the total displacement of the structure on the soft soil and does not have a major influence on the total displacement of the structure on the stiff soil. Also slope of the diagram is low enough that the reduction of total displacement of structural model with SSI effects laying on soils with wide range of shear velocities would not change significantly.

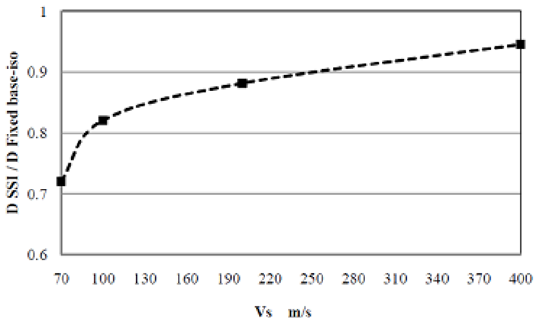

Figure 9. Ratio of total displacement considering SSI effects to total displacement without considering SSI effects

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Farzad Hatami, was born in Tabriz, Iran in 1977. He received the B.S. degree in civil engineering from the Tabriz University, Iran, in 2000, and the M.Sc. and Ph.D. degree in structural branch of civil engineering from the Khaje Nasir University (KNTU) and Amirkabir University if Technology (AUT) Tehran, Iran, in2002 and 2007, respectively.

In 2008, he joined the Iranian’s Research Institute of Petroleum Industry (RIPI), as an Assistant Professor, and in 2009 became head of post graduate research department. Since April 2010, he has been with the Department of Civil and Industrial Engineering of Research Institute of Petroleum Industry where he was head of this department. Since July 2014, he has been with the Structural and Earthquake Research Center (SERC), Amirkabir University of Technology, where he was an Assistant Professor as Director of Graduate Educational Group in construction management and structure engineering in e-learning education department. He has more than 32 Journal papers (as 2 hot papers in Elsevier), 63 Conference Papers, and 6 Books (For example: Steel and Composite Shear Walls, Advanced Strength Materials, New Construction Material in New Structural system, etc). His current research includes concrete and steel structures, base isolation, composite materials, shaking table, Bridge engineering, FRP materials, steel and composite shear walls and construction management projects.

Dr. Hatami is a Fellow of the Iranian Society of Civil Engineering (ISCE) as head of Educational Department; Iranian Society of Steel Structures (ISSS); and Iran Color Society (IRCS). He is a Committee to develop a charter member of the "Design and Construction of Concrete" *(topic Ninth Iran’s National Building Regulations)*, Member of the team's first elevated train project, Member of project design and construction team for shaking table, Member of Seismic upgrading project team studies Bridges of Tehran-Organization and Civil Engineering, and Editorial board of the Journal of Research in Iran (ASAS).

He was the vice president of the 4IBC International Conference on Bridge Engineering (4BC2015) held in Tehran, Iran. He was the recipient of the best paper Prize of the *Universal Researchers in Civil and Architecture Engineering (*URCAE2015)Awards for his contributions to the field of concrete engineering in December 2014, Best researcher Awards, Research Institute of Petroleum Industry (RIPI) in 2010, and Best Iranian Research Awards by Institute of Standard and Industrial Research of Iran (ISIRI) in 2008.

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