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Soil-Structure Interaction and Seismic Performance of Semi-rigid Jointed Steel Frame - A Review

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Abstract: The aim of this paper is to present the kind of work has been done on the topic 'Effect of Soil-Structure Interaction on Seismic Performance of Semi-rigid Jointed Steel Frame'. Large quantity of research work has already been done in this area using various methods. Nonlinear time history analysis, pushover analysis, finite element modelling and analysis etc. have been carried out by so many researchers. Nonlinear behaviour of soil base was also investigated considering influence of Soil-Structure Interaction (SSI) separately. But no such investigation is available which analyze seismic performance of structure considering both semi-rigid joint and SSI effect, leaving room for further studies.

Keywords: Seismic performance, steel frame, semi-rigid joint, soil-structure Interaction

1. Introduction

The seismic performance of a steel frame structural system depends on numerous factors such as its configuration and dynamic property and applied earthquake excitation. It is necessary to simulate all these factors close to reality in order to do correct evaluation of seismic vulnerability of a given structure. One of the important configurations is the beam-to-column connection i.e. joint. Mainly two type of joint are used commonly, rigid joint and pin joint. It is not possible to develop a steel frame with fully pin joints or perfectly rigid joints. Fully pin joints imply no moment transfer while perfectly rigid joints indicate complete rotational resistance. Experimental results show that true joint performance is in between these two simplified form. Pinned joints exhibit some moment resistance while rigid one possesses few degree of flexibility.

All engineered structure resting on the soil, founded on a load transmission interface called a foundation. So another important factor is energy transfer mechanism from soil base to superstructure during seismic excitation. It is nonlinear and dynamic in nature commonly known as Soil-Structure Interaction. During investigating the past earthquake and examine the seismic performance of structural frame it is noticed that SSI effects plays an important role. In spite of a wide spread research over last 40 year, the influence of SSI effect is still controversial as many documented evidence shows detrimental effect. It provides interest in studying the seismic performance of steel structure with semi-rigid joint considering SSI effect has beneficial role or has a detrimental role.

A large quantity of research work has been already done in this area using various methods. But no such investigation is available which analyze seismic performance of structure considering both semi-rigid joint and SSI effect, leaving room for further studies. Aim of our study to provide suitable answer to the questions like-

Is SSI effect beneficial or detrimental during earthquake excitation?

What will be the result of the combination of semi-rigid joint and SSI effect on seismic performance of structure?

2. Studies on Semi-rigid Connection

The structural performance of steel frame mainly depends on its connection's property. Due to this, the proper modelling of steel framed structure depends on accurate modelling of connection, if actual performance is desired to be achieved. Usually, it is considered that the connections between beam and column are either perfect pinned or completely rigid. Investigational tests, however, have shown the real characteristic of beam-to-column connections is somewhere in between these two unrealistic models. For realistic design or modeling, it is necessary to consider the connection behaviour as the third category; however, it is expected that most of beam-to-column connection shows semi-rigid response. Several research work that consist of numerical and experimental assessments have been done so far to establish moment-rotation relationship which is significant to estimate the ideal characteristic of semi-rigid connections. The outcome of these studies suggested that the seismic performance of steel frame highly depends on adequately designed semi-rigid beam-to-column connections. The findings also revealed that there is a direct link between connection stiffness and base shear; however, the lateral drift does not change linearly with changing the connection stiffness.

M.M. Kassem et al. (2019) introduce a seismic vulnerability index (SVI) methodology to evaluate reinforcement concrete building through nonlinear parametric analysis. In SVI, the maximum top displacement is basically determined using engineering demand parameter. Then the mean of SVI gives the value of physical damage of structure in a particular earthquake. K. Kamyar et al. (2019) investigates the response modification factor for hybrid cold-formed hot-rolled structure. They use nonlinear dynamic model to evaluate post-peak response of the knee-braced frames and standardized using experimental outcomes. Post-buckling characteristics of CFS studs are estimated using numerous methods like FSM, FEM, and AISIS-136-16 analytical formulation. This paper shows that initially assumed R-factor is appropriate for design. A. Asgharia and S. Saharkhizan (2019) investigate Knee-element Connections Frame (KCF) as a seismic-force-resisting arrangement. Seismic response of KCF is compared with special moment-resisting frame (SMRF) using FEMA P695 methodology. It concludes that though failure mechanism in both KCF and SMRF is similar but collapse possibility for KCF is less compare to SMRF.

F. Barbagallo et al. (2019) study seismic response of Buckling Restrained Braced (BRB) frame with semi-rigid connection. The finding of nonlinear dynamic analysis shows this type of connection develops a residual lateral stiffness on post yielding of BRBs leads to uniform spreading of the drift demand along the height.

A.C. Umare et.al. (2018) analyze and design the top and seat angle connection and beam-column connection performance for deflection and joint displacement. They examine the unsymmetrical structural model for different load combination using STAD Pro V8i software. It estimates relative spring stiffness of beam-column connection to evaluate semi-rigid characteristics of joints. J. Ruiz-Garcia et al. (2018) evaluate the seismic response of eccentrically braced frames. Under Mexico City Code criteria, they use analytical models to evaluate the nonlinear behavior of the links and failure criteria. Result shows that strong aftershocks could significantly increase inter-story drift demands once the link fails. G.A. Papagiannopoulos (2018) analyzes nonlinear time history seismic performance of 3-D tension only concentrically braced structure. He proposes a tension-only braced structure as seismic resisting system. J. Ruiz-Garcia et al. (2018) studies the response of 3-D steel moment-resisting frame having different story height against bi-directional attack with different PGA level. It is observed that the 3-D building model's response differs from the 2-D model response. This study shows that the 3-D modelling approach has significant influence to evaluating seismic response of steel.

A. Belleri et al. (2017) evaluate the appropriateness of using simplified building models as tools for seismic vulnerability assessment of existing steel frame. They show that this approach is suitable for identifying seismic deficiencies and load demand. V.H. Truong and S.E. Kim (2018) present a method to analyze the nonlinear characteristics of structure using time history analysis. Proposed method of optimization seems to be significant as it reduces the number of analysis required and also gives an optimum frame. M. Araujo et al. (2016) estimate the seismic vulnerability and property losses of industrial building. They include losses both structural and nonstructural parts of building. They took 10% probability of exceedance for 50 year for this estimation. M. Tehranizadeh and E.S. Rezvani (2015) evaluate seismic response of steel moment resisting frame structure considering non-linear soil structure interaction (SSI). It concludes that the SSI effect contributes to reduce the drift demands of the structure. G.N. Stamatopoulos (2014) investigates influence on seismic response steel frame structure due to semi-rigid characteristics of column base plate connection. Nonlinear dynamic analysis with three different type of model considering flexible column-base plate join due to yielding of joint material shows significant improvement of seismic response of structure. It concludes that semi-rigid characteristic of steel structure should be considered for design consideration as it has significant impact on seismic response.

R.S. Kumar and S.R.S. Kumar (2014) present seismic performance based design of semi-rigid composite framed structure. They analyze different model of structure using static and nonlinear pushover analysis. The outcome of the study shows that significant reduction of base shear can be attained using semi-rigid connections. H. Shakib et al. (2011) examine the seismic vulnerability and structural rehabilitation of semi-rigid jointed steel buildings. Findings of the seismic analysis indicate necessity of seismic retrofitting. Out of the three suggested retrofitting, it shows suitability of using concrete shear wall over other. X. Zhang and X. Zhao (2011) study seismic response of semi-rigid jointed steel frame. Finite element model of steel structure was prepared using ANSYS software by them. Seismic analysis result of the model with semi-rigid connection under synthetic excitation shows a notable change on ductility, natural period, internal rigidity and lateral displacement leads to overall improvement on seismic performance. D.M. Patil and K.K. Sangle (2015) investigate the seismic behaviour of 2-D steel frame with different bracing system. They use nonlinear pushover analysis to evaluate the seismic response considering different system in high rise steel building. The outcomes show that performance of braced system is better than the moment resisting frame system. M. Ebrahim and F. Danesh (2018) propose semi-rigid connection for long link to column to avoid failure. The experimental outcome shows the significance of introducing semi-rigid connection in eccentrically braced steel frame. I. Faridmehr et al. (2017) introduce stiffness matrix method to evaluate performance of semi-rigidly connected portal frame. The result shows that semi-rigid connections are responsible for energy dissipation due to which base shear reduces.

A. Pirmoz and M. Lue (2017) propose a facile displacement-based method to design the semi-rigid steel frame structures. The new method is based on the assumption that the plastic deformation is occurring only at the partially restrained joints and beams and columns are remain elastic. K.W. Ding and Y.Y. Bao (2016) obtain the seismic response and elastic time history of steel frame structure consisting rigid and semi-rigid joint using SAP2000 under earthquake excitation. The conclusion shows that the seismic performance of semi-rigid connection is better than that of rigid connection as it sufficiently increase the natural vibration period and displacement. But it also reduces stiffness of structure. M. Bandyopadhyay and A. K. Banik (2016) study progressive collapse of unbraced and braced frame both with semi-rigid joints. The study shows significance of bracing to resist progressive collapse and floor wise bracing are much effective than bay wise. Kiani et al. (2016) investigate seismic vulnerability and performance of semi-rigid jointed steel frame. They produce fragility curve to show vulnerability considering certain probability of exceedance for immediate occupancy, life safety and collapse prevention. They also suggest importance of seismic retrofitting of existing structure.

A. Mikaeili and S. Naimi (2015) introduce fragility curve for joints of steel frame. Based on connection failure criteria they draw fragility curve and compare with moment rotation curve. To specify performance level, they use pushover and cyclic loading curve. M. Najdian and M. Izadinia (2012) analyze seismic performance of semi-rigid steel frame with near-fault earthquake excitation. It compares the outcomes of rigid and semi-rigid jointed frame using nonlinear time history analysis. The result shows that semi-rigid connected frame have better response over other. Y. Lue et al. (2010) evaluate progressive collapse of steel building contains semi-rigid connection. The disengagement of member(s) due to connection failure is also considered in this study. The outcome of the study shows the significance of the method. A. Aviram et al. (2010) describe importance of assessing seismic performance, reliability and failure modes of column base connection. It also provides direction for performance based design and economic feasibility of a structure. S. Bo et al. (2011) studies seismic response spectra of semi-rigidly jointed steel frame. The outcome of the analysis shows the influence of joint characteristic on natural frequency and displacement of the structure. These enhance property of the structural system leads to improvement of overall seismic performance of structure. A. Reyes-Salazar et al. (2014) present effect of interior gravity frame (IGF) and perimeter moment resisting frame on nonlinear seismic response. The outcome of the experiment indicates that IGF significantly resist the lateral structural load.

F. Petruzzelli et al. (2012) describe the procedure of modeling and analysis for seismic resistance of an existing building. They point out some important issue like difficulty to modeling connection for column to base which is different from standardized form; effects of p-Delta, side sway global collapse etc. F. Namvari and P. Zarfam (2011) evaluate significance of modal pushover analysis (MPA) for semi-rigid jointed Knee Bracing steel frame. The outcomes are matched with dynamic nonlinear response history for that particular structure. The similarity of the results shows appropriateness of using MPA. A. Abolmaali et al. (2009) present energy dissipation characteristics of a semi-rigid joint. They get the outcome by performing the hysteresis loops obtain from 48 full scale cyclic experiments. C. D. Annan et al. (2009) study the inelastic performance of a modular braced steel frame. They evaluate significance of seismic energy dissipation due to inelasticity. This study shows adequacy of the structure within inelastic limit.

3. Studies on Soil-Structure Interaction

Seismic energy transform mechanism commonly known as soil-structure interaction is an important issue in the dynamic analysis for heavy weight and implanted structures like high-rise buildings, nuclear reactors, liquid-storage tanks, turbine towers etc. Usual design exercises for dynamic loading consider the structure to be rest on a fixed base. But experimental test results shows the associate soil medium undergo some movement due to its behaviour to distort. This may leads to reduction in overall stiffness of the structure and it could enhance the natural periods. This influence can alter the ultimate performance of the structure. The interaction between the structure, base of the structure and soil medium beneath the foundation can influence the actual response of the structural system considerably, as compare to response obtained considering the structure alone. Several research works have been executed to develop proper, realistic and easy to implement SSI models.

D.J. Choudhari and N.N. Chopade (2018) examine the effects of soil-structure interaction on seismic performance of building designed for life safety. The model of a RC building is designed as per IS 456:2000, analyzed using the SAP2000 software with two different constrain, fixed base i.e. without considering SSI effect, and flexible base i.e. considering SSI effect. They compare the seismic response and take average of peak response storey drift, storey shear, and natural period. It was concluded that the SSI can alter the seismic performance of building. K.S. Patil and A.K. Kakade (2018) study the seismic response of steel braced RC structure considering SSI effect. They show how these steel braces increase the horizontal stability and rigidity of structure. It also investigates the SSI effect and in what extent it influences the structural stiffness and natural period of the system. They use these outcomes to sufficiently strengthen the RC structure. A. Anvarsamarin et al. (2018) produce fragility curve for moment resisting frame considering SSI for seismic uncertainties. The outcome shows advantage of taking account of SSI effect. A. Matale and A. Khedikar (2018) experiment and analyze performance of existing pre-seismic design code building. In this paper, SSI has been considered and outcomes show that it has positive impact.

Y. Cai et al. (2017) derived two set of solution for in-plane SSI. One approach excludes boundary condition while other considers all the boundary condition. It also reveals the importance of boundary conditions. L. Wang et al. (2018) introduce a computational method to evaluate full scale 3D random vibration produce by railway traffic. The outcome from multi-point synchronous algorithm (MPSA) is compared with standard result that gives efficiency of this method. A. Rahmani et al. (2018) study reliability of seismic soil pile interaction using one dimensional uncoupled spring. It concludes that this method do not capture most of the mechanism, hence it results erroneous outcome. M. Aslmand et al. (2018) propose a method to evaluate 3D layered soil structure interaction using coupling an axisymmetric formulation. This paper shows that it can be applied to several SSI problems consisting foundation of irregular shape over layered soil. W. Zhao et al. (2019) study influence of the spile-soil interaction on seismic performance of steel bridge. A finite element model of a steel girder bridge considering spile-soil interaction has been analyzed. The study shows that its seismic performance is better as compared to the model without considering spile-soil interaction effects.

H.G. Kabtamu et al. (2018) examine SSI effect on multi-storey building with flexible and fixed base. They conclude that SSI effect is always not beneficial. P- Δ mainly depends on heavy gravity load. C.C. Mitropoulou et al. (2016) evaluate influence of SSI on fragility curve of structural frame. They produce fragility curve by using SCADA Pro software and then doing nonlinear static analysis. Observing the result, it is found that for low and mid-rise building SSI does not affect significant though quite important for high-rise building. H.I.M. Riaz et al. (2016) investigate dynamic characteristics of structural frame and impact of SSI over its seismic response. It shows the significant improvement in terms of natural period, base shear and story drift after considering the influence of SSI effect. F. Tajirian et al. (2014) examine seismic performance of steel gravity structure considering SSI effect. The analysis is carried out with state-of-the-art software. It shows due to heavy gravity load SSI has significant influence over base shear, overturning moment and maximum acceleration. P. Pattanashetti and M.S. Bhandiwad (2016) study effects of shape and plan arrangement of an irregular building based upon different soil condition. They compare the analytical outcome of building model for different soil base using ETABS software. It concludes that though there are various factors affecting the response of structure; soil condition plays an important role.

J. Seo and R. Shukla (2016) investigate the combined effect of seismic and scour fragility of existing steel building. They model the structure as per building specification available and consider SSI by introducing soil spring reflection. By using finite element software, the model was tested with forty eight different synthetic excitations for continuously reducing values of soil springs. The seismic response of the structure proved that SSI has great impact on vulnerability. Progressive soil spring shows increment on fragility. A.H. Varma et al. (2015) apply the nonlinear seismic soil-structure interaction analysis to identify the seismic margins at nuclear power plant site. In this study, seismic probabilistic risk assessment methods are intended to provide accurate estimation of the different combinations of equipmental and structural failures which lead to damage of structure. T.H. Lee and V.W. Lee (2014) develop a model for soil-structure interaction to represent a flexible foundation. They considered tapered shape semi-circular rigid foundation for structural modeling. They derive an analytical expression for this particular case.

S.E.A. Raheem et al. (2014) investigate the critical energy transfer mechanism under earthquake excitation from soils to buildings. They reveal that if SSI effect is neglected, it could be uneconomical design. They obtained numerical outcomes for SSI effect that are different from fixed base, shows its significance. A. Worku (2014) demonstrates significance of introducing SSI effect in building design. This effect lengthens fundamental period and hike effective damping. This paper elaborates that if this base shear reducing potential is used properly then it leads to a structural-work cost savior. Aydemir and Ekiz (2013) address the performance of multi-storey structural system considering SSI effect during earthquake. Experimental outcome shows strength reduction factor due to SSI is smaller than design code providing strength reduction factor. This proves that conventional design seems to be unsafe. F. Taddei and K. Meskouris (2013) investigate the changes on seismic response of wind turbine by considering the SSI effect during earthquake excitation for seismic hazard prone area. To analyze the system, models are prepared using finite element and boundary element methods. It estimates the influence of seismic performance of wind turbine due to dynamic characteristics of SSI. The findings are compared with response of simply idealized soil spring system. P. Raychowdhury (2011) studies seismic response of low-rise moment resisting steel building considering nonlinear SSI. This paper focuses on modeling and understanding this nonlinear SSI behavior using beam-on-nonlinear-winkler-foundation approach. The outcome of the study shows significant reduction in force and displacement.

M. Eser et al. (2011) analyze influence of SSI effect on strength reduction factor. They obtain elasto-plastic behavior for 20 earthquakes considering SSI effect. They compare effective period, damping and effective ductility value of fixed base. Difference of the outcomes shows significance of SSI effect. Y. Tang and J. Zhang (2011) evaluate the probabilistic seismic demand of shear wall considering nonlinear SSI effect. They produce a realistic numerical model of the shear wall and foundation and conduct nonlinear time history analysis. Experiment shows SSI effect is very sensitive to soil friction angle and it also influences damage probability of structure. S. Renzi et al. (2010) investigates SSI effect on seismic response of reinforce concrete shear building. To establish the significance of this effect, they produce a generalized model for shear type structure. The outcome shows positive result. Robert (2009) studies non-linear dynamic soil structure interaction (DSSI) phenomena. The result illustrates contribution of DSSI to reduce seismic structural demand.

4. Conclusion

From the above discussion, it can be concluded that a plenty of research works have addressed the seismic performance of semi-rigid steel frame structure. Also a large of numbers of research studies has already been done on energy transfer mechanism from soil to structure i.e. soil-structure interaction effect on seismic performance of structure. But it is not clear that in which case the SSI effect is beneficial and for which case it is detrimental for the seismic performance. A majority of the studies have investigated elastic response only for either semi-rigid joint or for SSI effect. It is also not mentioned anywhere that what will be the effect of SSI on structural seismic performance of semi-rigid jointed steel frame.

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