Response Evaluation of Steel Frame systems with Settlement Load under Seismic Excitation using Structural Health Monitoring

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SUMMARY

Due to uneven homogeneity of the soil in the ground, it is surely not possible to say whether a structure will stay as if it was constructed before. In addition, in the earthquake-prone area, certain degree of settlement is unavoidable even if the whole structure is constructed over a rigid base. Several studies have already proved that differential settlement poses a significant threat over the structural components like member strength, joints, supports and causes redistribution of internal forces of the structure. This study is focused on the modeling of simple frames having different story height to understand the response of the frame system in combination with seismic motion and settlement through structural health monitoring system (SHM) measurements. Furthermore, a comparison has been made between the settled and unsettled structures to understand the frame response under complex loads effects. This study provides that the main variable in structures collapse under complicated loads that including the settlement is the damage of structures systems.

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1. INTRODUCTION

While designing any structure, engineers initially simplify the load condition, use their engineering judgment, and come up with a solution that may fulfill the requirement. In practice, load determination is a complex phenomenon. Load nature may change due to location, architectural design or material property of the structure. Several loads that may consider when designing any structure. Among them, prior to design any structure the dead load and live load play a vital role. Under the service life of the structure, the foremost duty of any structure is to withstand those loads. Loading state may alter gradually, sometimes it changes abruptly. During construction or post-construction state, the structure may undergo deformation, experience artificial vibration, foundation settlement or displacement or earthquake excitation. If the structure cannot survive under those loads, we may call the structure is damaged. Internal stress within the member plays an important part in the stability and rigidity of the frame which usually generates during the construction phase and it may fluctuate due to uneven load distribution, displacement of the components, earthquake or column displacement. At present, structural engineers usually neglect any influence caused by vertical displacement of supporting columns over the structure during their design stage or post-construction stage. But this assumption is very conservative although it may help to avoid complex calculations.
It's been inevitable for any structure to undergo changes due to presence of corrosion, degradation of the component or the loss of stiffness at the joint over the service life, sudden heavy load like earthquake, tsunami, cyclone, etc. may aggravated the health condition of the structure and may resulting into loss of life and property. In this circumstance Structural Health Monitoring (SHM) system provides the necessary information for the user and may help to understand the up to date condition of the building in a suitable manner.

2. PREVIOUS STUDIES

Most of the study consider that there will be no settlement until the construction of structure is finish, which is not true all the time. Settlement or displacement of the foundation during and after the construction may cause significant damage of structure and can create financial problem for owners and contractors. Settlement is broadly classified in two most common category uniform and uneven settlement. Uneven settlement of foundation is considered to be most critical. Uneven Settlement or vertical displacement of column pose deformation on the building and cause internal stress. Differential settlement effects load transmission and rearrangement of forces in the members which depends on the stiffness of the members and the magnitude of the settlement (Meyerhof, 1953). Absolute and differential settlement may occur in any building due to its design flaws and constructional faults which may aggravated due to the construction of adjacent structures (Anastasopoulos, 2013).

It is also necessity to consider the change of stiffness along the structure during construction stage. Magnitude of internal governing stress while any part of the structure undergoes vertical displacement relative to other parts of the building solely depending on the flexibility of the building (Gauld, 2014). Considering the frame as flexible in the case of low structure can be a suitable assumption but cannot suitable for high-rise buildings which have short span and deep member sections (DeJong & Morgenstern, 1971). High stiffness of the frame has consequence over column load and moment which transferred to the ground and can be redistributed to adapt or mitigate the settlement. Incremental dynamic analysis shows acceptable indication among the earthquake intensity and structural collapsible probability for uneven foundation settlement structure where it is found that settlement at the corner cause serious damage as well as increase story drift whereas influence of settlement at center area has lower seismic response due to stable and strong restraints by nearby region (Bao et al., 2019). Settlement cause substantial damage at adjacent structural components and this condition aggravated by creating plastic hinge and elastoplastic component due to the increasing of the intensity of the earthquake. Research also showed that differential settlement and seismic intensity has influence over horizontal seismic response independent to settlement location and amount which are also intensify the probability of collapse and decreases safety resistance of seismic collapse (Bao et al., 2021). Settling column experiences tensile force where compression force generated in adjacent column meanwhile significant bending moment and relatively small shear force has been developed in adjacent beams of the building structure to minimize this effects researcher suggested to introduce higher safety factors while designing stage of the components (Lin, Hanna, Sinha, & Tirca, 2015). Differential settlement not only create significant problem in the building structure but also in continuous dynamic loading structure like rail road (Yi, Jinshen, & Xu, 2019).

Damage of structural system may introduce the change of natural period, mode shapes dynamic response, etc. Vibration based damage identification method can be classified into four categories natural frequency, mode shape, curvature mode shape and both mode shape and frequency (Fan & Qiao, 2011) among them changes of natural frequency and mode shape commonly used. Cracks, corrosions, creep, cyclic loading, aging, loss of tightness of bolted joints, fatigues, etc. which characterizes damage cases within any structural system can be represents as a stiffness loss of the structural system (He & Zhu, 2011). Conventional damage detection procedure like vibration technique observe the changes of modal property of the system which can suffer due to environmental and functional condition and may misguide the expert as a damage in the structure(Casas & Moughty, 2017).

Recently, structures health monitoring (SHM) systems have been widely used to guide the engineers to monitor structures members to detect damage as well as help to reduces the cost of quality control, minimizes the production time and improve in design process which results into a suitable structural management system (Castañeda-Saldarriaga, Alvarez-Montoya, Martínez-Tejada, & Sierra-Pérez, 2021; Schubel, Crossley, Boateng, & Hutchinson, 2013). In case of super tall structure, SHM system can be a suitable tool to determine the settlement condition of the structure under construction stage and provide predicted settlement value after completion of the project which can also precisely give the elevation value of high-rise building (Su, Xia, Xu, Zhao, & Zhang, 2014). In high speed railway bridge, intelligent SHM system has also being used to detect the settlement in order to ensure the satisfactory operation under high speed dynamic condition (Yi et al., 2019). Several SHM system has also been used for long

period of time or even twenty-four hours a day to assess different types of practical structures near active earthquake zone and harsh wind condition located in Chile, Japan and China (Boroschek, Villalpando, & Peña, 2019; Fujino, Siringoringo, Ikeda, Nagayama, & Mizutani, 2019; Ou & Li, 2010; Sumitro & Wang, 2005).
Therefore, this research investigates to study the response of a three-story steel frame model under 10mm differential displacement/settlement condition having damage and healthy case over fixed seismic linear actuator. Here damage and health case represent as loosened and tightened bolted connections at one side of the support system. 10 mm settlement at the base level column that has being applied by considering adjustable angle which are connect the base of the actuator with the column of the frame system.

3. FRAME DESCRIPTION

Prefabricated three storey shear building frame model shown in Fig-1 made from SUS304 stainless steel having length 250mm, width 180mm and 1035mm height. The composition consists of a column member, a floor member, and a member that holds the two. 110g weigh column is highly flexible having 340mm height 34mm width and 1.2mm thickness. Plate at each story have 1800g weight 250mm by 180mm dimension and a thickness of 5 mm. Plate and column at each story has been connected by angle (50g) of having one pair of holes which are used to connect both plate and column. The frame is designed in such a way that three story frame model have three degree of freedom system. To collect the response data from frame system iLOG-ACC-MEMS-WNN-3CH sensor has been used which can provide acceleration data in 3 direction at 150 & 200Hz by using Wi-Fi-system.

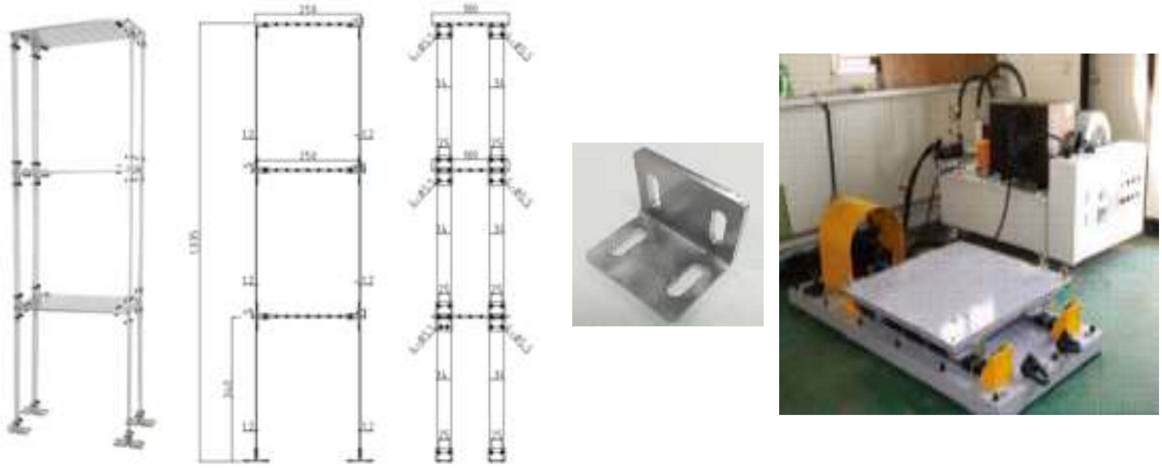

Fig.1: Three-Dimensional Frame Building, Adjustable Angle, Hydraulic Actuator

Two sensors have been installed in the frame model, one was supported at the top floor, another in the base of the hydraulic actuator to collect the input seismic data. For the seismic analysis hydraulic servo vibration tester was used which have compatible design for big and heavy specimen can produce above ***1g*** acceleration and consists of hydraulic servo actuator, vibration table, hydraulic pump, servo valve, accelerometer, operational program various of jig and components. In this study, the El Centro north-south earthquake has been used in the part of analysis for the settlement and without settlement frame model under damaged and healthy condition.

4. EXPERIMENTAL STUDY RESULTS AND DISCUSSION

The input earthquake has been shown in the Figure 2 which has been filtered through 2^{nd} order Butterworth Bandpass filter. The filter was considered to pass and stop band frequency 0.1 to 70Hz, respectively. The dominant frequency of the frame in healthy condition under free vibration is 1.5625Hz.

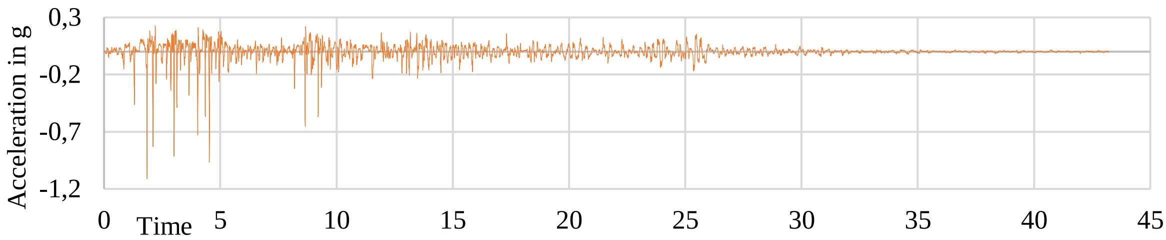

Figure 2. Input Earthquake Acceleration

Figure 3 and 4 illustrates the collected filtered data of frame performances in the damaged and undamaged cases, respectively. In both cases, the complex loads were employed. It has been found that the healthy frame generates higher acceleration value (*0.8601g*) compare to (*0.7502g*) unhealthy frame where only settlement has been incorporated (Figure 3). In frame model that has already being damaged as a loss of tightness of the bolt under settlement condition produce lower acceleration (*0.4675g*) than having no settlement condition (*0.5274g*) as shown in Figure 4.

From analysis data it can be seen that all the response from the frame model have three peaks which represents three mode shape of this three-story frame model. Figure 5 shows that the dominant frequency without any damage and having no settlement is 1.5625Hz, while considering settlement without having any damage it found out that the frequency reduces to 1.4893Hz. Which implies that due to settlement of the frame model a considerable damage has been occurred and it affected the dominant frequency of the frame.

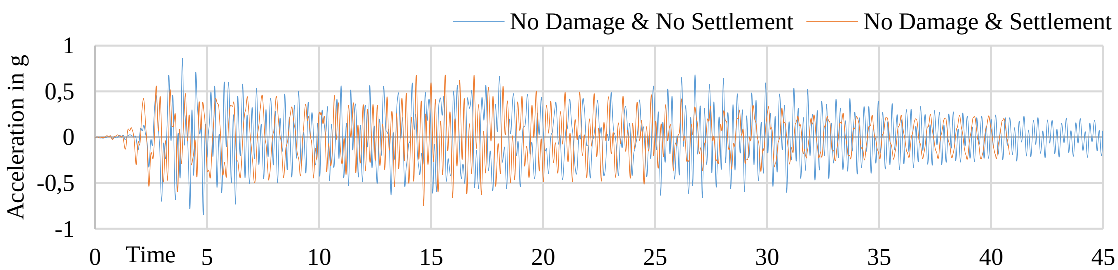

Figure 3. Settlement influence over frame response under no damage condition

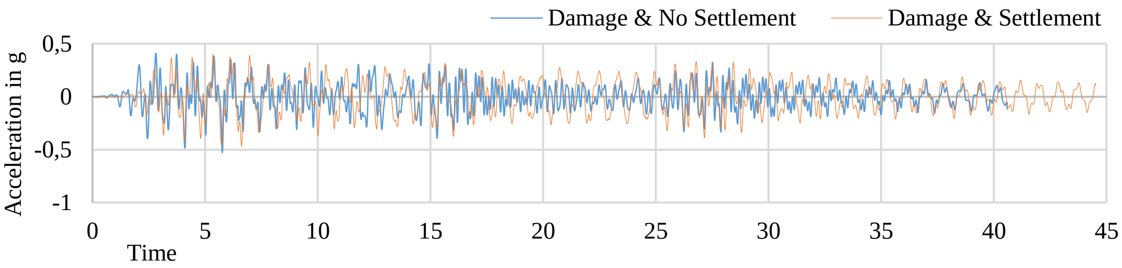

Figure 4. Settlement influence over frame response under damage condition

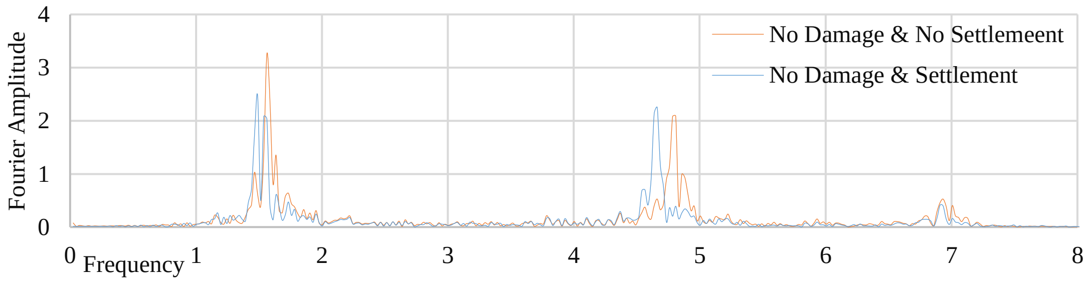

Figure 5. Settlement influence over frequency response without any damage

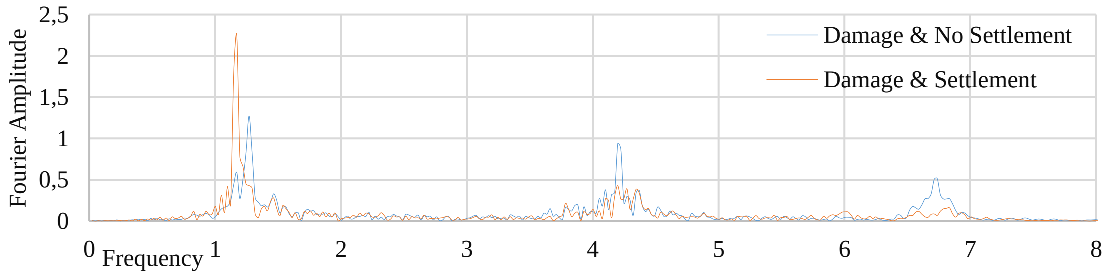

Figure 6. Settlement influence over frequency response with damage

On the other hand, having damage without any settlement in the frame model under earthquake condition produce frequency about 1.2695Hz while considering both damage and settlement condition generate less response around 1.1719Hz (Figure 6.).

From these results it can be seen that damage in the frame system in terms of loss of tightness of bolt and settlement significantly reduces the frame response. In case of damage frame model, the reduction of the response is higher compare to the settlement frame model which indicates that settlement have low influence over frame response than damage due to the looseness of the bolt connection. The rigidity of the frame model decreases due to the presence of both conditions. Summary of different cases has been shown in Table 1 from which it shows that health frame has higher acceleration at top of the frame and high dominant frequency whereas presence of damage and settlement create less acceleration at the top and reduce the dominant frequency as well. From the table data it has also found that damage has higher influence over settlement. Having no damage and 10mm settlement at the foundation level create higher acceleration at the structure compare to having damage and no settlement condition. Frequency value also changes from 1.4893Hz to 1.2695Hz. Which indicate that rigidity of the frame is highly affected by damage compare to settlement in this highly flexible frame system.

Table: 1- Acceleration and Frequency at different case study

Case Study	Acceleration in g	Frequency in Hz
No Damage & No Settlement	0.8601	1.5625
No damage & Settlement	0.7502	1.4893
Damage & No Settlement	0.5274	1.2695
Damage & Settlement	0.4675	1.1719

5. CONCLUSIONS

From experimental data, it can be easily understood that settlement in terms of displacement and damage as a result of loss of tightness of bolted joints at base of the column have influence over response of the frame model. Due to settlement the response of the frame has slightly changes from healthy structure. Frame response under damage condition have higher influence over settlement state. Under the damage condition like loss of tightness of the bolt at base level create more frequency loss compare to only settlement condition. If both conditions have been considered it has been found that frequency of the frame will decrease higher which means either damage or settlement frame system possess damage in the system of the frame model.

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