Earthquake Damping Device for Steel Frame

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Abstract: Structures such as buildings, bridges and towers are prone to collapse when natural phenomena like earthquake occurred. Therefore, many design codes are reviewed and new technologies are introduced to resist earthquake energy especially on building to avoid collapse. The tuned mass damper is one of the earthquake reduction products introduced on structures to minimise the earthquake effect. This study aims to analyse the effectiveness of tuned mass damper by experimental works and finite element modelling. The comparisons are made between these two models under harmonic excitation. Based on the result, it is proven that installing tuned mass damper will reduce the dynamic response of the frame but only in several input frequencies. At the highest input frequency applied, the tuned mass damper failed to reduce the responses. In conclusion, in order to use a proper design of damper, detailed analysis must be carried out to have sufficient design based on the location of the structures with specific ground accelerations.

1 Introduction

Earthquake is a dangerous natural phenomenon that occurs due to a change in the tectonic plate motion. Strong shaking of the ground can cause massive destruction on engineered structure, for example, skyscrapers, roadways, dams and bridges. However, the consequences can still be handled by designing the structure properly in order to lessen the damage.

One of the ways to lessen the damage is to install damper in building for vibration control. Passive control dampers such as Tuned Liquid Damper and Tuned Mass Damper are most common damper installed as they are easy to design, reliable, efficient as well as environmentally friendly [1]. In this study, the effects of tuned mass damper on a two-story simple frame structure are investigated experimentally using finite element model.

1.1 Problem Statement

This project highlights the performance of damping device as an earthquake reduction product. The rubber product is introduced as a damping device to support Malaysian rubber to become high-end industry. Even though Malaysia has low to moderate seismic risk, seismically active neighbouring countries such as Sumatera may activate the inactive fault lines in Malaysia. Sabah, compared with Sarawak and the Peninsular, is the riskiest as it has the most active earthquake fault lines. For example, Ranau was struck by strong earthquake with magnitude 6.0 at Richter scale that caused the death of 18 people in 2015. Throughout the seismic history, the potential to experience massive earthquake in Malaysia is high. In that case, installation of damper on buildings are recommended in order to prevent or minimize damage due to earthquake since destruction of buildings without warning put people’s lives at risk.
1.2 Objectives
The objectives of this study are:

i. To study the behaviour and design concept of tuned mass damper to structure.
ii. To investigate the dynamic response of simple frame structure by comparing laboratory test and finite element model.
iii. To identify response of frame with and without damping device.

1.3 Scope of Study
In this study, the effectiveness of TMD as a single structural response controller device will be determined. The parameter for TMD has been used in the laboratory as well as in the Finite element modelling using SAP2000 software. Through experiment and software modelling, the results for frame structure with and without damper will be achieved. The design parameters for the TMD are based on the mass ratio of the structure and damper. In experimental test, spring has been used as a component of the TMD. Excitation of different frequencies has been applied to the structure using harmonic table shaker and the direction is in horizontal axis. Acceleration and displacement responses of the simple frame structure during the harmonic test will be taken for both frame with and without damper. Performance of the structure for both models has also been analysed using finite element model. The outcome for both finite element and experimental study has been compared and the effectiveness of TMD were determined.

2 Literature Review
2.1 Potential seismic activities in Malaysia
In general, Malaysia is considered as a geologically stable country. However, Malaysia is close to the Indian-Australian and the Eurasian plates on the west which are very active seismically. There is no doubt that Malaysia is exposed to earthquake risks. In this perspective, peninsular Malaysia has experienced tremors from local origin earthquakes and massive earthquakes that occurred at the plate boundary area especially at the Sumatran fault [2]. The most likely to be hit by earthquake in Malaysia is Sabah which has approximately 13 seismic active faults [3]. Earthquakes that occurred nearby the inter-plate boundary between the Philippine Sea Plate and the Eurasian Plate on the east were felt in the East Malaysia. An earthquake with a magnitude more than 7.8 has the ability to transfer the seismic waves through a distance of approximately 700km [4]. Peninsular Malaysia is roughly around 350 km away from the seismically active area. In 2015, 18 people was killed as a result of earthquake occurred in Ranau, Sabah with magnitude of 6.0, one of the most powerful earthquakes recorded in Malaysia. According to a geologist from Sabah, Dr Felix Tongkul, the Ranau earthquake occurs approximately every 25 years. Consequently, Malaysia should consider to build or modify structure that can sustain strong vibration.

2.2 Design concept of Tuned Mass Damper
The concept of TMD is basically when a device with a mass installed in a building or structure moves with a phase shift at the same frequency as the structure. Usually, a spring-dashpot system supports the mass to securely attach to the buildings. The mass attached will transfer its inertial force to the structure in a direction opposite to the movements of the structure itself, by that the structure's oscillations reduced. Mechanism of TMD system that attached to the structure includes a mass, a spring, and a damping device. The formula from the law of physics, \( F = ma \) and \( a = F/m \) proves that acceleration exists when external force is applied to the TMD on a building. Structure tends to sway when external force is applied, but the TMD also will produce force that at the same time moves opposite to the direction of the structure until the natural period of TMD is near to the fundamental period of structure and eventually the horizontal displacement at zero [5].

2.3 Effectiveness of Tuned Mass Damper
TMD is a special device that dissipates a significant amount of energy of a structure and have been implemented throughout the world to control movements of structure. However, based on previous studies, under seismic excitation, the function of TMD depends on the characteristics of the earth's surface movement [6]. Vibration response of structure is effectively reduced by TMD only when the earth's surface motion shows narrow band of frequencies and long period of time [7]. They studied that under high intensities of ground movements, the performance of TMD in reducing the responses of buildings may significantly decrease because of nonlinear reaction of the buildings. Conversely, different from linear systems, the
effectiveness of TMD considered only by using peak reaction of nonlinear buildings is insufficient [8]. The effectiveness of TMD to reduce damage of structures under low nonlinear vibrations should be considered [9]. In that case, study the response of buildings with the installation of multiple tuned mass dampers attached to it. As a result of their study, multiple TMDs system are more effective to overcome high intensity vibrations due to seismic load.

3 Methodology

3.1 Proposed design
There are two sorts of responses of frame that need to be compared, which are acceleration and displacement when applied with different values of frequencies from both experimentally and by using finite element modelling. For laboratory work, harmonic test will be carried out. The structure that will be used is a multiple degree of freedom (MDOF) steel frame with a dimensions of 0.83m length, 0.83m width and 2.25m height along with total mass of 148kg. The loading on the frame is based on the limitation and ability of the steel material to sustain it. Software known as SAP2000 will be used as a main mechanism to analyse frame which is highly recommended as it allows formation of computer models of structure and examining physical response of structure to evaluate a design without having to build and destroy numerous models in testing. The effectiveness of the tuned mass damper are determined after result from experimental work are verified using SAP2000 software.

3.2 Experimental test
The two storey structure frame is firmly fixed onto the harmonic table platform and the loading of 50kg is applied on each level. As a means to analyse the application of damper on structure for this analysis, harmonic test will be done for frame structure without damper under different ground acceleration input values of frequencies. Three accelerometer devices are needed to be attached on the harmonic table, on first floor and on the top of the frame. The function of the device is to measure the response of a structure on the harmonic table in terms of acceleration and displacement. Seismosignal software is used to analyse the data from the device and to obtain the natural frequency and natural period as well as the resonance of structure. Next, the damper will be installed at the same structure and tested again with the same frequencies as shown in Figure 1. The design of damper is shown in Figure 2 for clearer view. Comparison of the responses acquired between the frame with damper and the one without it will estimate the effectiveness of the damper. The data received using accelerometer will be analysed in Seismosignal. The example of acceleration time history analysed in Seismosignal is provided in Figure 3.
3.3 Finite element model
The data that was obtained from designing of the prototype has been used for finite element modelling process. By using finite element of SAP2000, the natural frequencies as well as the interrelated vibration modes of the damper can be obtained. In this software, the accuracy of the model analysis can be determined by referring to the modal participating mass ratio which will show the percentage of static and dynamic in all related directions. If the percentage is high, it shows that the modelling is very precise. Therefore, to identify the behaviour of frame structure with damper in this study, the frame analysis is conducted in finite element modelling of SAP2000 and it also considered as a verification method for the harmonic test. This analysis will be done for the frame with and frame without spring damper by using the finite element modelling of SAP2000 software at every frequency, similar to experimental test.

3.4 Comparison of results
For free vibration analysis, the natural period and natural frequencies are compared to get the difference in percentage of response for frame structure with and without damper for both analysis methods. If the percentage is small, it shows that both methods are accurate and dependable when conducting free vibration analysis. It also indicates that both harmonic test and finite element model of SAP2000 are effective ways to investigate the dynamic behaviour of structure. The response of frame is based on the harmonic laboratory test and finite element model of SAP2000, the acceleration and displacement of frame at several frequencies are the results which will be compared. If there is a percentage of reduction obtained from these results at several frequencies when spring damper is installed in the structure, it indicates that the response of the frame can be reduced by installing the spring damper.

4 Result And Discussion
4.1 Laboratory testing under Harmonic Excitation
4.1.1 Response under Free-Vibration. The most important parameters in order to reflect the dynamic characteristic and flexibility of structure are known as the natural frequency, \( f_n \) and natural period, \( T_n \). Table 1 shows the response of frame structure under free vibration for both models. The natural frequency and natural period percentage difference obtained between both models is 2.7% which is quite small and adequate. The difference is due to the additional weight of TMD which altered the response of frame.

| Table 1 Response of frame structure under free vibration. |
|----------------------------------------------------------|
| Response | Without TMD | With TMD | Percentage of different (%) |
| Natural frequency (Hz) | 1.71 | 1.76 | 2.7% |
| Natural period (s) | 0.585 | 0.569 | 2.7% |

4.1.2 Acceleration response of top frame. Graphs of maximum absolute acceleration for the models are presented in Figure 4 for clear overview about the effectiveness of TMD. The graph shown shows that the best performance of damper was at the input frequencies of 0.48Hz to 1.22Hz, but fail to reduce the acceleration at input frequencies of 1.47Hz and 1.72Hz.

Figure 3 Acceleration Time History in Seismosignal for 1.22Hz at the ground level
4.1.3 Displacement response of top frame. In the case when the frame is at resonance, the percentage of reduction of displacement response is within -30.8% for both models which is similar to the acceleration response. From the result, the installation of TMD on frame structure is not an effective way to lower the maximum absolute displacement at resonance condition but it is effective at the input frequency of 0.98Hz. The TMD effect comparison graphs of maximum absolute displacement for both models are shown in Figure 5.

4.2 Analysis with Finite Element Model

4.2.1 Response under Free-Vibration. The percentage differences of natural period and natural frequency between both models are 6% and 12.5%, respectively, based on the summary of results presented in Table 2. The difference is due to the added mass of TMD since it is influenced by the mass, m and the stiffness, k of frame structure.

4.2.2 Response under Input Ground Acceleration

Acceleration of Top Frame. In Figure 6, at the first input frequency, the acceleration difference for both modals is high. The damper shows the best performance at input frequencies of 0.48Hz until 1.22Hz, similar to harmonic test analysis.
Figure 6 Maximum absolute acceleration of frame in SAP2000

Figure 7 Maximum absolute displacement of frame in SAP2000

Displacement of Top Frame. The maximum displacement for SAP2000 analysis in Figure 7 shows that there is a reduction of displacement in input frequency of 0.98Hz while displacement at other frequencies shows the opposite.

4.3 Result Comparison

4.3.1 Free Vibration Analysis. Results for both analysis methods are presented in Tables 3 and 4. Based on the result, the percentage difference between two analysis methods is quite small. Hence, the two methods are reliable for conducting test to investigate the dynamic response of structure under excitation.

| Response          | Harmonic Test | SAP2000 | Percentage difference (%) |
|-------------------|---------------|---------|----------------------------|
| Natural Period (s)| 0.5851        | 0.5691  | 2.7                        |
| Natural Frequency (Hz)| 1.710      | 1.673   | 2.2                        |

Table 4 Free vibration response of model with TMD

| Response          | Harmonic Test | SAP2000 | Percentage difference (%) |
|-------------------|---------------|---------|----------------------------|
| Natural Period (s)| 0.5689        | 0.497   | 12.6                       |
| Natural Frequency (Hz)| 1.758      | 1.572   | 10.6                       |

4.3.2 Frame Response. The highest maximum and displacement response of the structure for both models is at 1.72Hz. Structure is at resonance at this frequency. The analysis shows that TMD has the capability to reduce response of structure towards excitations at certain frequency. However, it can be seen that the results for harmonic test is larger than results obtained by finite element model. This is because the material properties of the element in SAP2000 might not be similar to the material used during harmonic test and disturbance due to noises from the laboratory during the harmonic testing.
4.3.3 Peak Ground Acceleration. Peak ground acceleration can be defined as the maximum ground acceleration at a location where earthquake occurred. Based on the peak ground acceleration of Malaysia, the maximum acceleration occurred in West Malaysia and East Malaysia is between 0.041g to 0.082g and 0.061g to 0.102g, respectively. From the laboratory test, the highest ground acceleration achieved for frame without TMD was 0.1254g which is more to the peak ground acceleration of Ranau, Sabah. In this case, the damper used is not suitable to be implemented in civil structure in Ranau area. However, this damper can be recommended to be used for the buildings in West Malaysia in certain location. The experimental test peak ground acceleration output is presented in Table 5.

Table 5 Laboratory test PGA output for frame

| Control Frequency (Hz) | Excitation Frequency (Hz) | PGA (g)   |
|-----------------------|--------------------------|-----------|
| 5                     | 0.24                     | 0.00391   |
| 10                    | 0.48                     | 0.00939   |
| 15                    | 0.73                     | 0.02515   |
| 20                    | 0.98                     | 0.04258   |
| 25                    | 1.22                     | 0.09220   |
| 30                    | 1.47                     | 0.09272   |
| 35                    | 1.72                     | 0.12541   |

5 Conclusion
From the data and results obtained throughout the study, after conducting the analysis and several discussions, the conclusion can be made. The various frequencies on harmonic laboratory testing and finite element analysis modelling are conducted to evaluate the effectiveness of TMD on steel frame are successfully done. The results shows that the TMD absorbed the energy and the free vibration response were reduced. The time history response of structure are also reduced with TMD model.

Based on the result obtained and the peak ground acceleration for Malaysia, the damper is suitable to be used for structure in West Malaysia but only at certain places in East Malaysia. This is because the highest peak ground acceleration obtained from laboratory test is 0.1254g at input frequency of 1.72Hz. The peak ground acceleration in Ranau, Sabah area is around 0.13g, which is larger than the peak ground acceleration at 1.72Hz in harmonic test. The damper did not show any reduction in acceleration at this frequency. However, at frequency of 1.22 Hz, the peak ground acceleration is 0.09220g and at this frequency the response of frame towards acceleration was reduced with the presence of TMD. The peak ground acceleration is bigger than the peak ground in West Malaysia. Therefore, structure in West Malaysia and at certain places in East Malaysia can be installed with this damper to overcome the effect of external force vibration.

5.1 Recommendations
i. For future study, damper with different masses should be tested few times to get the best damper that can balance the motion of structure.
ii. The material properties in finite element model should be similar to that tested in harmonic test.
iii. Find the finite element model and laboratory test percentage difference and if it is less than 80%, analysis of finite element modelling should be done first.

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