The dynamic load test of two seismic resistance of steel structures EBF and RBS

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Abstract. The non-destructive dynamic loading test has been conducted on two seismic resistance of steel structures, reduced beam section (RBS) and eccentric braced frame (EBF). Eccentric mass shaker was used to excite the 1-storey 1-bay steel structure. Two dynamics parameters were obtained which were the natural frequency and the damping ratio. A finite element analysis was performed using OpenSees software to get a comparison result. Similar natural frequency and displacement response were obtained from the test and the FE Analysis. The Natural frequency of RBS and EBF was around 3.614 Hz which is similar to the FE analysis as 3.623 Hz. Meanwhile the damping ratio is 3.149%. The natural frequency of the EBF structure is around 6.0 to 6.13 Hz, while the FE analysis result is 6.13 Hz. The damping ratio from test results is between 2.04 – 2.06%.

1. Introduction

Seismic resistance structural system has been developed for decades and steel structure have several varieties. The concept of the system is by designing the weaker part as a place of energy dissipation during earthquake which is named as plastic hinge. Special Moment resisting frames (SMRF) and Eccentrically braced frame (EBF) are two of seismic resistance system for steel structures.

SMRF which is known as reduced beam section (RBS) was proposed to enforce the form of plastic hinge away from the panel zone by designing RBS as the weaker section. The beam flange is cut in circular radius on the top and the bottom of flange to reduce the area at the beam end. Hence, the plastic deformation form there resulting the energy dissipation during earthquake. Several research about RBS has been carried out since 1996 and during the last ten years the research still have been done to improve its performance. [1],[2],[3],[4],[5],[6].

The EBF combines the high elastic stiffness characteristic of a concentrically braced frame (CBF) and the energy dissipation stability of a moment resisting frame (MRF). The system consists of a link which is designed as a weaker section to allow the plastic deformation. The longer link allows energy dissipation through flexural yielding while a shorter link dissipates energy through shear yielding. Shear yielding allows for the development of plastic deformation without the formation of excessive local strain, which is prevalent in flexural yielding [7]. Shear yielding provides a larger energy dissipation capacity than flexural yielding [8]. For that reason, there are three parameters that must be considered when designing an EBF system: bracing configuration, link length, and link section properties. In long links—often referred to as flexural links—yielding occurs only in the ends of the link where plastic hinges form. It is for this reason that EBF systems with shear links are more stable and more ductile than flexural links. However, for architecture reason, the flexural link is preferable since this system allows for a larger clearance than that of shear link EBFs.
As part of seismic resistance structure, several research about the two systems have been conducted for years but limited research have been reported about the dynamic test of those system. For an economic reason, FEM modelling has been used to obtain the dynamic characteristics of several structures. An effort has been done to get an accurate identification with development of experimental tools to make health assessment of existing structures is more economics and the damage can be easily detected. Eccentric mass shaker (EMS) is one of the innovative tools that can generate excitement for a large building, which is commonly called forced-vibration tests (FVTs). In the last few decades, dynamic tests have been used to obtain the dynamic parameters of structures [9],[10],[11,12]. The parameters are natural frequency, mode shape, and damping ratio. The natural frequency can be used as an indicator for detecting structural damage by examining the decrease in natural frequency [13].

This research aims to investigate the dynamic parameters of the one storey of the RBS and EBF system through FVTs. Eccentric mass shaker was used to induce the sinusoidal dynamic force. Two modal parameters, natural frequency and equivalent damping ratio were obtained.

2. Materials and methods

The test was conducted on a knock down frame that was purposely designed to support the dynamic test of two systems, the RBS and the EBF. The main frame consists of a 3m-length column, beam and composite slab. A WF300x150x6.5x9 was used for the column which is connected to a WF150x75x5x7 for beam on column weak axis. A composite slab with 100mm-thick was constructed on top of metal deck at an elevation of +2682mm. RBS was connected to flange of the column by three end plate system to ensure a rigid connection. Detail of RBS is shown in figure 2. A gap as 200mm was provided between RBS and the composite slab to prevent the composite action. The slab was meant to provide a mass source and to locate the EMS.

![Figure 1. Top View of the Frame](image)

The test was conducted twice, and it was started with the RBS followed by the EBF. The RBS was uninstalled when the second test was conducted. The EBF system was located on the elevation of +1341mm. Detail of EBF system is shown in figure 3. The beam of EBF was constructed by WF200x100x5.5x8 whereas the links use WF70x35x3x5. Double angle profile 2L50x50x5 was chosen for bracing. All the steel material was used grade BJ37 where the yield strength was 235MPa. The steel modulus of elasticity was 206MPa.
The load was induced by Eccentric Mass Vibrator System (EMS) MK-139-10. It was a sinusoidal load with a frequency identical to the structure’s natural frequency. The EMS uses a two-armed drive system that produces a single-directional force. The force exerted by the vibrator can be calculated using the following equation:

\[ F = MR(2f \pi)^2 \]  

where \( F \) is the exerted force in Newton, \( MR \) was the eccentricity in kgm unit and \( f \) is the vibrator rotational velocity (Hz). In this test, the structure was induced by a load of 0.11625 kgm at a frequency of 1-15 Hz. A lighter load was used to identify the elastic response of the structure. The structural response obtained was the mode shape and the damping ratio.

The structural response was recorded using vibrometer and accelerometer. The accelerometer can capture response in all directions, longitudinal (X), transversal (Y) and vertical (Z) meanwhile the vibrometer only measured the longitudinal direction according to the laser shooting and at this test the sensor was fired into the centre of the beam as shown in figure 3.

![Figure 2](image1.png)
**Figure 2.** Side View of the Frame and frame the picture.

![Figure 3](image2.png)
**Figure 3.** Detailing of EBF.

![Figure 4](image3.png)
**Figure 4.** The sensors.

3. Results and discussion
3.1. Test Results of RBS
The structure was induced by sinusoidal forces twice. Firstly, the force frequency was increase in large increment and secondly, the frequency was increased smoothly near to the natural frequency of the structure. All recorded responses were the acceleration in time-domain which then were converted into a frequency domain based on the Fast Fourier Transformation (FFT) by SIGVIEW software. The natural frequency of the structure was obtained by looking at the peak frequency of the Frequency Response Function (FRF). Figure 5 show on example of recording from the first test in time domain and the results after converting to frequency domain is presented in figure. The measurement from two test were compared and presented on Table 1. As can be seen the measurement of accelerometer and vibrometer was very close and the average natural frequency from the test was 3.5933Hz.

There are two methods to determine the damping ratio, using the half-power bandwidth method and logarithmic decrement method. The results from the two methods are slightly different. The average damping ratio from two measurements using the logarithmic and the half-power bandwidth is 3.149% and 3.219% respectively.

![Figure 5. Velocity vs time response obtained from the vibrometer in the first test](image)

![Figure 6. FFT results in structure responses in a function of the frequency of the first test](image)

| Test   | Frequency (Hz) | Damping Ratio (%) |
|--------|----------------|-------------------|
|        | Vibrometer     | Accelerometer     | Vibrometer     | Accelerometer     |
| 1st Test | 3.5625         | 3.6168            | 3.553%         | 3.0810%           |
| 2nd Test | 3.6000         | 3.5939            | 3.553%         | 2.9645%           |
| The average | 3.5812         | 3.6053            | 3.4195%        | 3.0138%           |
The dynamic FE analysis using OpenSees software was conducted for further analysis. Non-linear beam column element was used to model the column and the beam. Concentrated plastic hinge was assigned to represent the RBS. Properties of plastic hinge were defined by rotational spring based on Ibarra Modified Krawinkler (IMK) \[2\] to describe the nonlinear behaviour of the frame.

The dynamic load applied in the FE analysis was selected from the test which produced the maximum displacement respond as 0.618mm. The part is shown in figure 5 which is in the red box. The time domain forces were then converted to the frequency domain to get the frequency of the force. The value was 3.6111Hz based on the first test, then the sinusoidal forces with similar frequency was applied to the FE model. The displacement responds based on the FE analysis was 0.619mm which was similar to the test results as 0.618mm. It can be concluded that the FE analysis with OpenSees can imitate the dynamic test very well.

Further analysis was carried out to get an inelastic respond of the RBS. The load was applied with a frequency close to RBS natural frequency which was 3.62 Hz. This value was equal to an eccentricity of EMS (MR) as 40 kg-m or equivalent to lateral load as 20.71kN. The result was presented on figure 8. As can be seen, the RBS reached the plastic zone where the ultimate load was much higher than the force applied (20.17kN). It can be explained that the RBS experienced resonance since its natural frequency was equal to the frequency of the external forces.

![Figure 7. The FE model of RBS](image)

![Figure 8. Non-linear response of RBS based on FEA](image)

3.2. Test Results of EBF

Similar with the first test, the EBF was test twice, under free vibration and force vibration. Figure 9 and 10 show the reading of accelerometer #1 under both conditions. The signal obtained in time domain was then converted to frequency domain. The natural frequency and the period of the EBF based on accelerometer #1 was 6.049 Hz and 0.165s, respectively. Using the half-power bandwidth method, the calculation of damping ratio is presented in figure 11 which is equal to 2.06%. The summary of natural frequency and damping ratio based on measurement from accelerometer #1, #2 and #5 and the vibrometer is listed on Table 2. The average natural frequency is around 6.09Hz whereas the damping ratio is about 2.04%.
The FE analysis using OpenSees was carried out as a comparison. According to the experiment, the EBF was categorized as a flexural link. Steel02 was selected for steel material which is a uniaxial Giuffre-Menegotto-Pinto model with isotropic strain hardening. Truss element was assigned for bracing. Beam and column used the NonlinearBeamColumn element that assumes plastic deformation to be distributed along the element. Link was defined with BeamWithHinges command, where the plasticity is concentrated at the end of link.

The damping ratio:

\[
\xi = \frac{f_B - f_A}{2f_r} = \frac{6.2 - 5.95}{2 \times 6.04938} = 0.0206 = 2.06\% 
\]

**Figure 9.** Acceleration vs time from accelerometer #1, under free vibration

**Figure 10.** Acceleration vs time from accelerometer #1, under forced vibration

**Figure 11.** The calculation of damping ratio based on accelerometer #1 under free vibration conditions using the Half-Power Bandwidth Method.
Table 2. The test results of EBF.

|                | Frequency (Hz) | Damping Ratio (%) |
|----------------|----------------|-------------------|
| Accelerometer #1 | 6.049          | 2.06%             |
| Accelerometer #2 | 6.111          | 2.04%             |
| Vibrometer      | 6.111          | 2.04%             |

Similar loading condition as applied on the experiment was used. The excitation with a light load of 0.11625 kgm was induced with gradually increasing frequency. The structural response was in the elastic stage. The displacement reading from the vibrometer was used to compare the FEA and the experiment. Figure 12 shows the vibrometer response where the minimum and the maximum displacement was 0.73 mm and 0.98 mm, respectively thus having a displacement of 0.855 mm. The FE results is shown in figure 13. The displacement obtained is almost similar to the experiment which is 0.853 mm.

Figure 12. Displacement vs Time from vibrometer response

Figure 13. Displacement vs Time from FE Analysis

4. Conclusion
The force vibration test can be conducted by using the EMS. The linear dynamic response obtained from the test are the natural frequency and the damping ratio. The natural frequency of the RBS steel frame is about 3.614 Hz which is similar to the FE analysis as 3,623 Hz. Meanwhile the damping ratio is 3.149%. Similar displacement response was attained from the test and the FE analysis.

The natural frequency of the structure gain from the test is around 6 – 6.133 Hz, while the FE analysis result is 6.13 Hz. Moreover, the damping ratio based on vibrometer and accelerometers measurements is between 2.04 – 2.06%. The elastic displacement obtained from the experiment is 0.855 mm which is almost identical to the displacement from the FE analysis as 0.853 mm. The
dynamic response conducted using FE software OpenSEES is potent in modeling a steel RBS and EBF structure with harmonic excitation.

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