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Dynamics Analyses of Swing Structure Subject to Rotational Forces

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Abstract**—**Large-scale swing has been used in entertainment and performance, especially in circus, for a very long time. To increase the safety of this type of structure, a thorough analysis for displacement and bearing stress was performed for an extreme condition where a full cycle swing occurs. Different masses, ranging from 40 kg to 220 kg, and velocities were applied on the swing. Then, based on the solution of differential dynamics equation, swing velocity response to harmonic force was obtained. Moreover, the resistance capacity was estimated based on ACI steel structure design guide. Subsequently, numerical analysis was performed in ABAQUS to obtain the stress on each frame of the swing. Finally, the analysis shows that the expansion of swing structure frame section was required for mass bigger than 150kg.

Keywords**—**Swing structure, displacement, bearing stress, dynamic loads response, finite element analysis.

I. Introduction

ACTUALLY, not only in the developed countries but also in developing countries such as Cambodia, Thailand and Vietnam, the domain of entertainment has been increasing: the Eagle ride, Kingda ka, Top thrills Dragster, Dodonpa and especially swings structure which required attention and thorough analysis to increase the safety of this structure type. Due to the safety requirement, government agencies, park entertainment agencies, and researchers are strongly interested in increasing the safety of this structure [1]. Therefore, to perform a thorough analysis, dynamic performance of the structure was investigated based on dynamics of structure by Chopra [2].

Fig. 1 Swing structure

In this study, the response of swing structure subjected to harmonic rotational forces was the main interest. Moreover, frames of swing structure were focused with yield stress, and sections of the frame that were selected to analyze are popular in the market and for structural engineer usage. The parameters considered in this study were different masses from 40 kg to 220 kg and velocity that were applied on the swing to determine stress of the steel frame.

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II. Swing Structure Modeling

A. Steel Frame Geometry

Based on design plan and dimension of each frame in the structure, as shown in Table I, the swing structure model was developed in commercial finite element analysis software ABAQUS. Fig. 2 shows the model of the swing structure in this study, frame sections from Table I were indicated in the figure.

TABLE I
DIMENSION OF EACH FRAME STRUCTURE

No.	Shape	Section (mm)	Thickness (mm)	Length (mm)
1	Square	100×100	3.2	3,000
2	Rectangular	100×50	3.2	3,500
3	Rectangular	100×50	3.2	1,500
4	Rectangular	100×50	3.2	500
5	Round	R25	25.0	1,500
6	Round	R24.3	3.0	3,300
7	Round	R24.3	3.0	1,811

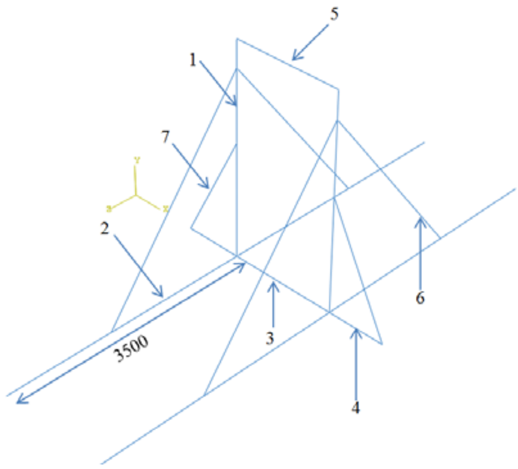

Fig. 2 Swing structure model in ABAQUS

B. Steel Frame Properties

Material properties for steel frame was based on ASTM A500, which is a standard specification published by the ASTM and is commonly specified in the USA. Therefore, material properties of steel use in this study had a specific gravity of approximately 7.85, and a density of approximately 7850 kg/m^3. In this table, grade A, grade B, grade C and grade

D, are strength material of steel.

TABLE II
YIELD STRENGTH OF STEEL [3]

Grade	UNS	Yield Strength (MPa)	Elongation (%)
A	K03000	269	25
B	K03000	317	23
C	K02705	345	21
D	K03000	250	23

C. Loading Conditions

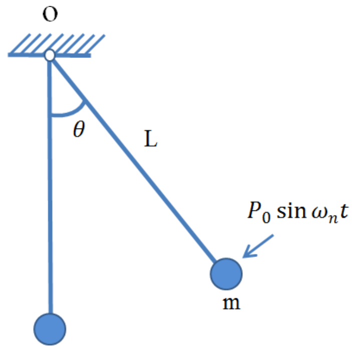

Fig. 3 Swing subjected to external force

Swing movement can be present with a simple pendulum as shown in Fig. 3 where the applied loads on the swing are t:

- $P_o sin\omega_n t$ is the harmonic force
- mg is the person weight

III. METHODOLOGY OF ANALYSIS

A. Swing Response to Rotational Forces

Dynamics of structure was used to determine velocity of swing subjected to rotational force (V). The velocity of swing was determined by the following equation motion [4]:

$$mL\ddot{\theta} + mg\theta = P_0 \sin \omega_n t \quad (1)$$

Initial condition $\theta(0) = 0$; $\dot{\theta}(0) = 0$

$$\theta(t) = -\frac{P_0}{2mg}\,(sin\omega_n t + \omega_n tcos\omega_n t) \quad (2)$$

$$\dot{\theta}(t) = -\frac{P_0}{2mg}\,\omega_n(2cos\omega_n t - t\omega_n sin\omega_n t) \quad (3)$$

$$\ddot{\theta}(t) = -\frac{P_0}{2mg}\,\omega_n{}^2(3sin\omega_n t + t\omega_n cos\omega_n t) \quad (4)$$

where $P_0 \sin \omega_n t$ is the external harmonic force [5], θ is the angle, $\dot{\theta}$ is the angular velocity, $\ddot{\theta}$ is the angular acceleration and V is the velocity of the swing ($V = \dot{\theta}L$).

B. Analysis of Reaction on Point O

Reaction on point O equal to tension (T) on the string is shown in Fig. 5. This reaction force could be calculated with the equation of motion in (5) [6]. Subsequently, the load transfer to the frame of the swing is shown in Fig. 6.

$$T = m\frac{V^2}{L} + mgcos\theta \quad (5)$$

$$\Longrightarrow F = T = m\frac{V^2}{L} + mgcos\theta$$

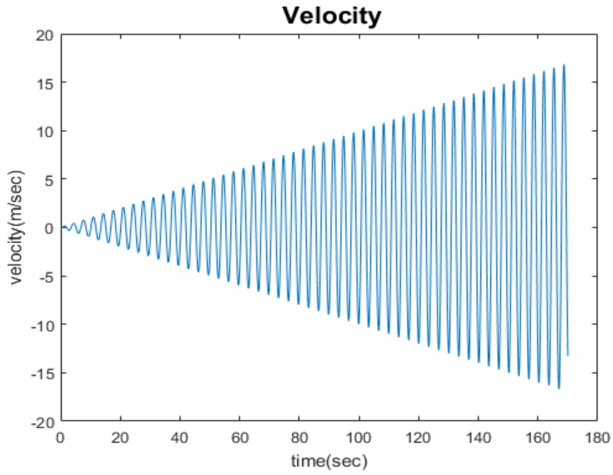

Fig. 4 Velocity of swing response to external harmonic force

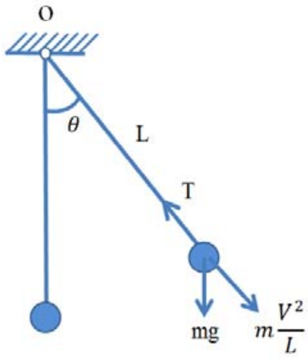

Fig. 5 Reaction force on point O

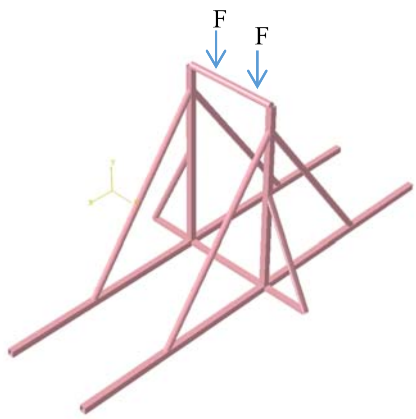

Fig. 6 Force applied on swing

IV. RESULTS

A. Finite Element Analysis Contour Results

After performing finite element analysis with ABAQUS, stress contour was shown in Fig. 7. In this figure, the critical frame could be seen on the upper beam of the swing structure.

Likewise, in Fig 8, the result of frame deformation was shown. In this figure, the maximum frame deflection occurred in the middle section of the upper beam element.

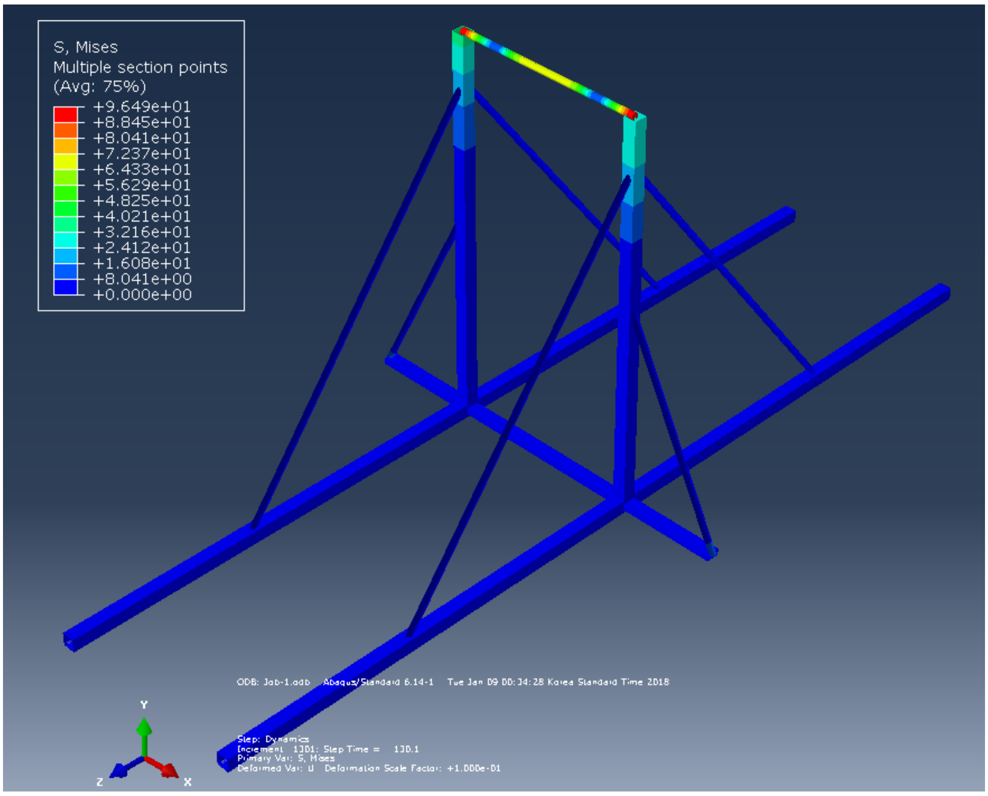

Fig. 7 Result of stress in critical frame (80 kg)

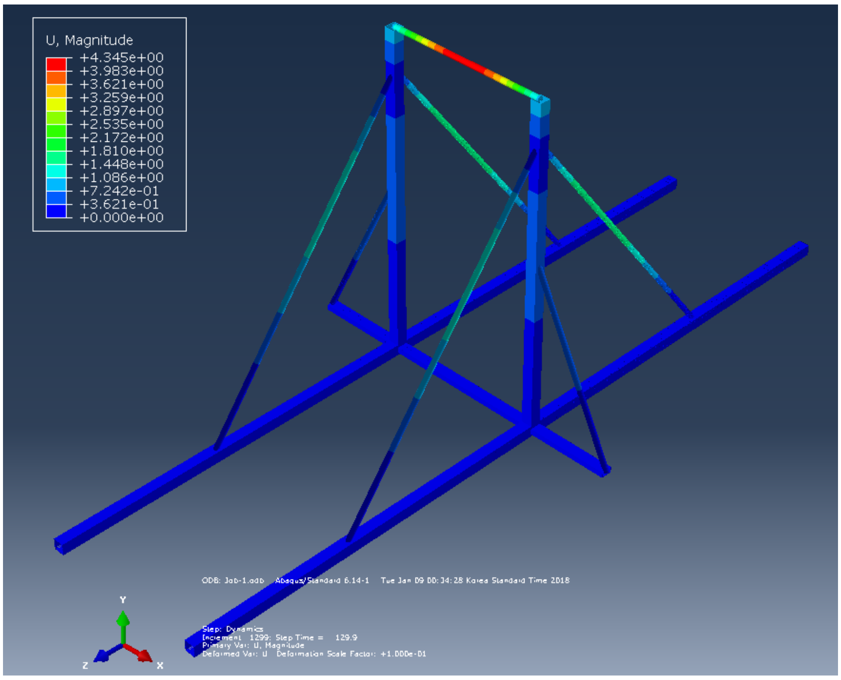

Fig. 8 Result of deflection in critical frame (80 kg)

B. Results of Analysis

Based on the stress contour result, we could plot the deflection of the critical frame in term of weight applied on the swing. Fig. 9 shows this plot results in blue (diamond marker) line and also the deflection limit in orange (square marker) line.

The deflection limit value was based on British Standard of Steelwork [7]. Graph in Fig. 9 shows that the frame deflection where the applied weight was between 40 kg to 150 kg was lower than the deflection limit graph. However, the deflection of swing's upper beam has a higher value than the deflection limit.

TABLE III
RESULT OF STRESS AND DEFLECTION

Weight (kg)	Stress (MPa)	Ratio (%)	Deflection (mm)	Ratio (%)
40	51.35	0.69	2.34	0.69
60	74.21	0.77	3.39	0.78
80	96.49	0.92	4.34	0.85
100	105.3	0.87	5.1	0.75
120	121.06	0.86	6.78	0.87
140	140.44	0.88	7.83	0.88
160	159.17	0.74	8.88	0.91
180	215.41	0.91	9.75	0.91
200	237.54	0.92	10.72	0.90
220	259.04	1.00	11.86	1.00

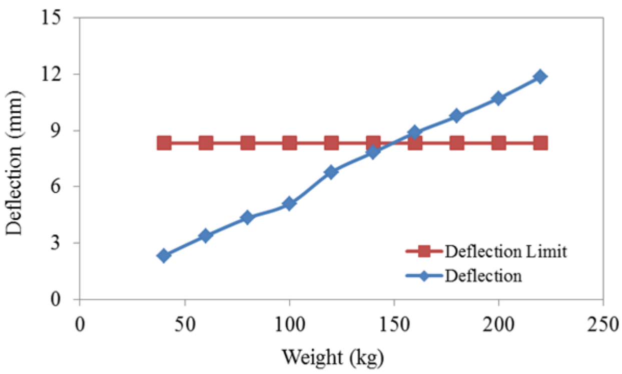

Fig. 9 Graph of deflection in term of applied weight

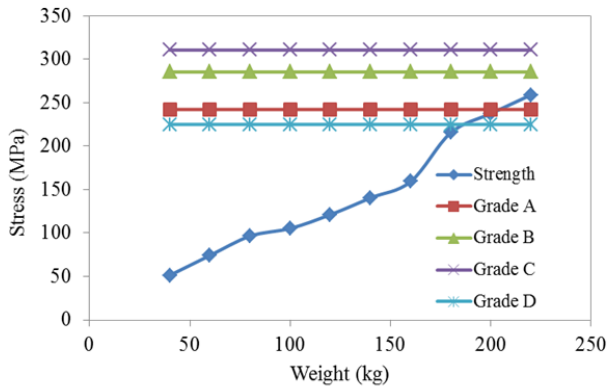

Fig. 10 Graph of stress in term of applied weight

Similarly, Fig. 10 presents the relationship between stress and weight graph. From this graph, we observed that when the weight was between 40 kg and 180 kg, the limit strength [7] was bigger than the required stress, but when the weight was over 205 kg stress required was greater than grade A and grade B but smaller grade C and grade D. Based on Fig. 9, although weight from 150 kg to 180 kg limit stress is greater than require, we need to increase dimension of steel. For grade C and grade D, their strength is higher than the required stress, however, required deflection is greater than limit deflection, so it is not recommended to use these grades.

V. CONCLUSIONS

In this study, the swing structure subjected to dynamics rotational force was chosen as the target structure for dynamic response analysis. Moreover, the deflection and bearing stress was verified for the critical frame which located in the upper beam of the swing structure. Four types of steel grade were selected to compare with the require strength. The results show that the frame section assign for model in this study was suitable for weight between 40 kg and 150 kg. However, for higher applied weight, the frame section of the swing structure needs to increase accordingly.

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