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Investigation on strength safety conservation of the roller coaster car support structures

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Abstract. In general, the long-term use of the support structure of roller coaster cars consisting of steel structures presents a safety problem with dynamic loading. In the past we have solved this problem in various ways. In this paper, after measuring and simulation using mobile acceleration sensors, motion simulation program ADAMS, and structural analysis program ANSYS, the support structure is considered as a system of connectivity, and the most suitable displacement and the optimal section of support structural brace to ensure the strength of the roller coaster car support structure is determined.

Keywords: acceleration, displacement, dynamic, strength, safety

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1 Introduction

Since the normal operation of the roller coaster car has begun and after a certain period of time, failure of the roller coaster car support structure has occurred and technical safety [1] can't be ensured, thus hindering normal operation [2]. Research has been carried out to solve this problem, and the analysis has not been performed by accurately reflecting the nearest-to-reality behavior, including the fact that the supporting structural columns were considered as independent column and the inertial force was applied as static load [3].

Hence, it has been seriously proposed to solve the problem of ensuring the stiffness stability of the support structure and the impact problem during the operation [4]. Increasing the radial horizontal displacement of the upper level of the support structure decreases the shock and proposes the strength safety at a time and vice versa [5]. That is, reducing the radial horizontal displacement of the upper level of the support structure increases the stability of the support structure, but serious problems arise, such as increasing the level of impact imposed on the

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roller coaster car, breaking the guide wheel and rail fastener and causing the users to feel uneasy [6].

Therefore, this paper determined the reliable radial horizontal displacement of the upper level of the support structure which can simultaneously ensure the stiffness stability of the support structure while minimizing the impact imposing on the roller coaster car.

2 Determination of the rational displacement threshold value of the roller coaster car support structure

2.1 Measurement of the response to the variation of the support column brace section

When the operation of the roller coaster car, the support structure will have a radial horizontal displacement in the first turn [7]. So at this stage of operation it is necessary to determine the reasonable displacement value of the support structure which minimizes the impact on the roller coaster car while ensuring the stiffness stability of the support structure [8].

To this end, after the roller coaster car starts, the responses in the 22-bearing column that lie in the most unfavorable position in the first turn are determined.

At first the responses (acceleration and displacement) were measured during the replacement and reinforcement of the lower portion of the brace with the most severe fracture in the 22-column support by the several sections. Acceleration was measured by a smartphone acceleration sensor, while displacement was measured using the visual information processing method [9] [10] simultaneously with the surveyor.

The dynamic characteristics were measured and the average responses were recorded by operating a roller coaster car for more than 10 times each time the braces of the support structure were replaced [11].

The measurement results are presented in detail in figures 1 and 2.

Figure 1 Acceleration Sensor Mounted at The Upper Part of The Support Structure

Figure 2 A Surveyor Installed For The Horizontal Displacement Measurement of The Support Structure

1. When a 19mm diameter reinforcing bar is used as a brace (Figure 3 and 4).

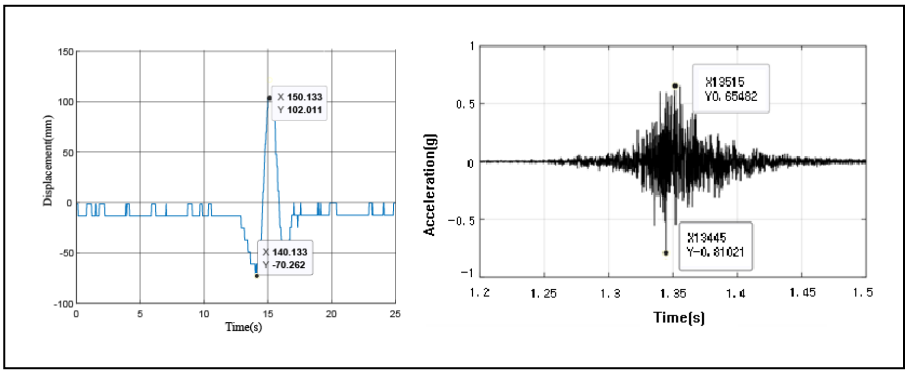

Figure 3 Fig 3. Responses of Support Structure (Displacement, Acceleration) When 19mm Bar is Used as A Brace

The maximum acceleration in the radial direction of the roller coaster car is 0.81g and the maximum displacement is 102.1011mm.

As can be seen from the measurement results, because of the large value of the radial horizontal displacement of the support structure, the impact on the roller coaster car is small, but the relative strength safety of the support structure is not ensured, thus greatly hindering the operation of the roller coaster car [12].

Figure 4 Butt Weld State of 19mm-Brace

2. When Angle rolled-steel shape75×5 bar was used as a brace (Figure 5).

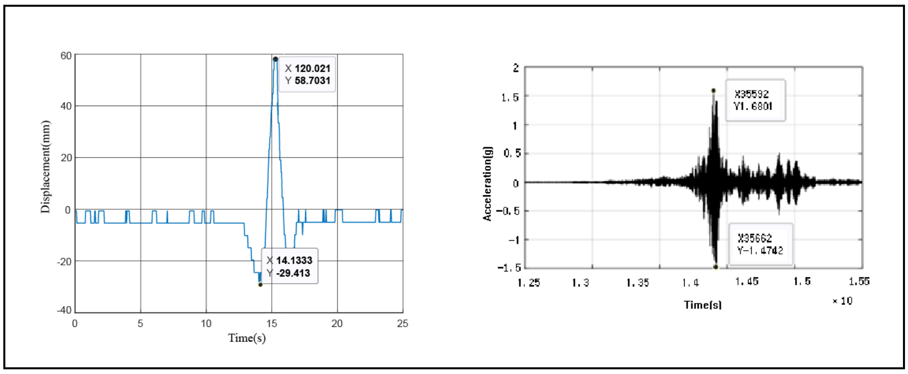

Figure 5 The Response of The Support Structure When Angle Rolled-Steel Shape75×5 Bar is Used as A Brace (Displacement, Acceleration)

Then the radial maximum acceleration of the roller coaster car increased 2.07 times with 1.68g and the maximum displacement decreased 3.8 times with 26.3mm. After the replacement of the brace with Angle rolled-steel shape bar, more problems were encountered when 19mm steel was used.

After the roller coaster car goes by the corresponding support structure, the tension brace is compressed by the roller coaster car, which has a great influence on the strength of the support structure, with a certain degree of resistance to compression (Figure 6).

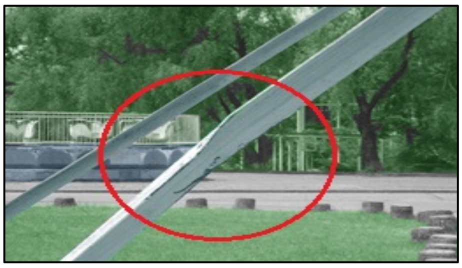

Figure 6 Deformed Bar With Buckling When it Compresses

3. When a 19mm diameter reinforcing bar is used as a brace (Figure 7).

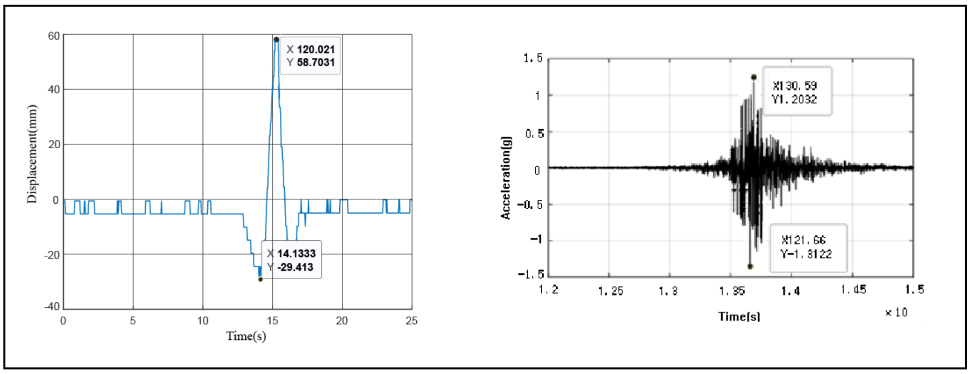

Figure 7 Responses of Support Structure (Displacement, Acceleration) When The Brace Diameter is 32mm

The maximum acceleration in the radial direction is 1.312g and the maximum displacement is 58.7mm. Screw bracing devices were used for the aim of deliberately controlling the horizontal displacement of the support structure while replacing all the brace with 32-mm reinforcing bars each (Figure 8).

Figure 8 The Brace With Turnbuckle

Since the 32-mm reinforcing bar was used as the brace of the supporting structure, the previous serious defects were completely eliminated. Therefore, the radial horizontal displacement value of the upper level of the support structure is determined by a reference of 58.7mm and the correct displacement threshold is identified by measuring the comfort of the roller coaster car users.

2.2 Identify the rational displacement threshold of roller coaster car support structure

Standard the horizontal maximum displacement of 58.7mm≈ 60mm at the upper level of the support structure and incrementally increase the displacement from below maximum displacement value, 26.3mm≈30mm to determine the rational displacement threshold through the comfort of the users. When turnbuckle was rounded a turn, the support structure was shifted 14-16mm horizontally, so the turnbuckle was turned to control the displacement and the average value was recorded by measuring acceleration and comfort (Table 1).

The available capacity of the roller coaster car is 24 persons with six vehicles, four for each vehicle.

Table 1 Acceleration and Comfort Measurement According to Displacement Control

No	displacement(mm)	acceleration	the comfort level (10 persons) Yes/No	Number of turn(time)
1	30	1.650g	0/24	4
2	35	1.634g	4/20	4
3	40	1.587g	10/14	4
4	45	1.491g	19/5	6
5	50	1.371g	24/0	6
6	55	1.318g	24/0	4
7	60	1.311g	24/0	4

As shown in Table 1, it can be seen that the comfort of roller coaster car users started to improve significantly after adjusting the horizontal displacement value of the upper level of the support structure to 45mm, and was completely improved after controlling 50mm.

Hence, a reasonable horizontal displacement threshold of the support structure is set to 50mm and the exact horizontal displacement value of the upper level of the support structure is re-determined through both the real and dynamic simulations to ensure the safety of the support structure.

3 Analysis modeling of roller coaster car support structure

3.1 Data measurement for analysis modeling

The total weight of the roller coaster car is 940 kg, the distance between the vehicles is 2.3m and the total weight of the six vehicles is 940×6=5640kg.

There are 4 people in one vehicle and 24 people in six vehicles in total. Thus, the total weight of the roller coaster car during operation is 5640＋1440＝7080kg, about 7000kg＝7t(70kN).

The tensile test data for the support column materials in the first turn range are as follows [13] [14] [15]. The yield limit of the column material is 350Mpa, the ultimate strength is 460Mpa, the yield limit and ultimate strength of the brace material is 275Mpa, 425Mpa respectively (Figure 9).

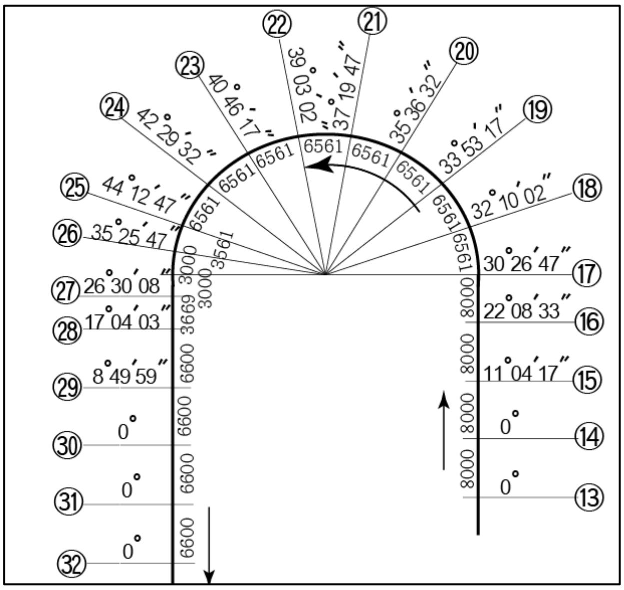

Figure 9 A Plan of Roller Coaster Car Support Structure in The First Turn Area

3.2 Analysis modeling and validity

The analysis model is constructed as shown in figure 10.

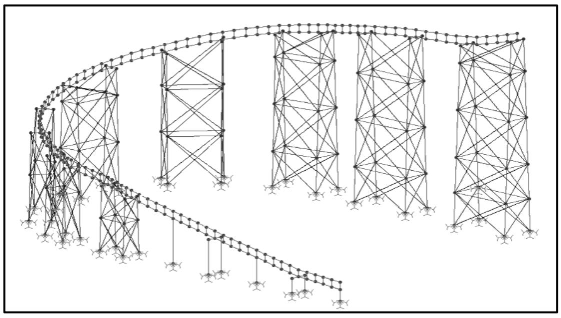

Figure 10 analysis model of support structure

Each bar is modeled as a single element. All members comprising the support structure of a roller coaster car are solved by geometric linear, material linear elastic bar elements. However, the brace is treated as a geometrical linear, material nonlinear elastic truss element that is only tensile and does not resist compression because the cross-section is very small compared to its length and works only in tension. The other element is given by a linear elastic material model (Fugure 11, Table 2 and 3).

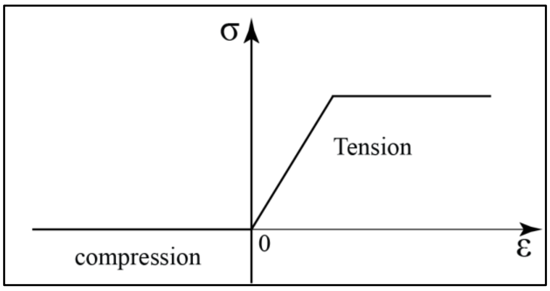

Figure 11 Nonlinear Elastic Material Model Characteristic Curve

Table 2 Linear Elastic Material Model [13]

material characteristics	material characteristic values
density	7860(kg/m^3)
Elasticity coefficient	2.0e11(Pa)
Poisson's ratio	0.28

Table 3 nonlinear elastic material model [13]

material characteristics			material characteristic values		
density			7800(kg/m^3)		
Poisson's ratio			0.28		
stress (Mpa)	-500	-250	0	250	500
strain (mm)	0	0	0	1.19	2.38

The constraint of the column base is solved by a hinge. In reality, the column-fixed bolt nut shifted 3-4mm upwards and downwards during operation, but was fixed in the analysis model and only considered in the analysis results. Because displacement of the columns is very small as 3-4mm, the effect on the horizontal direction of the upper level of the support structure is not negligible.

Summarizing the above analysis modeling process, the analysis model of the considered object is a combination of nonlinear elastic material large strain dynamics and rigid body dynamics problems.

4 Optimization scheme for strength and stiffness of support structures

4.1 Simulation analysis to ensure stiffness of the support structure

The most representative part of the failure in the roller coaster car support structure is the tensile brace at the base of the column 22, and the simulation analysis of various behavior using the motion simulation program ADAMS is as follows (Figure 12-14).

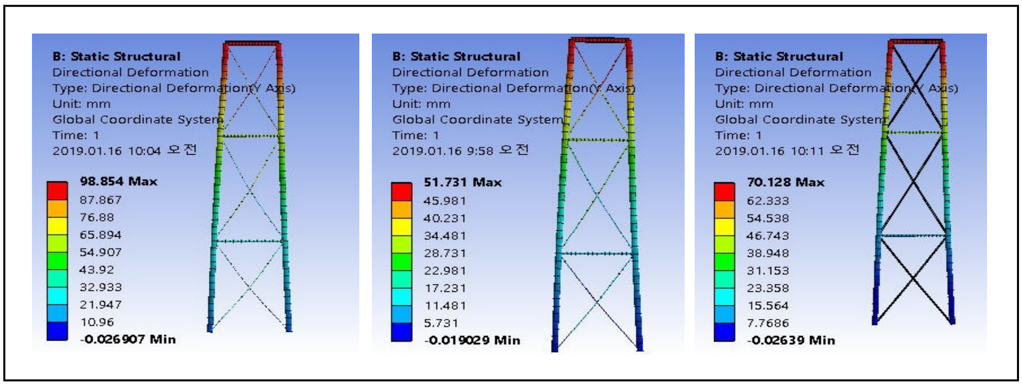

Figure 12 (a) The Case That The Brace Works Only in Tension (Reinforcing Bar- Φ19mm, Φ32mm, Angle Rolled-Steel Shape 75x5)

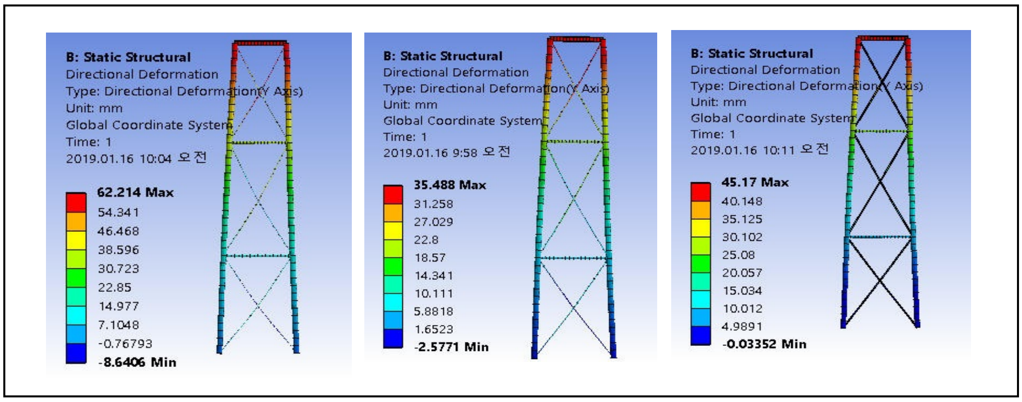

Figure 13 (b) The Case That The Brace Works in Tension or Compression (Reinforcing Bar- Φ19mm, Φ32mm, Angle Rolled-Steel Shape 75x5)

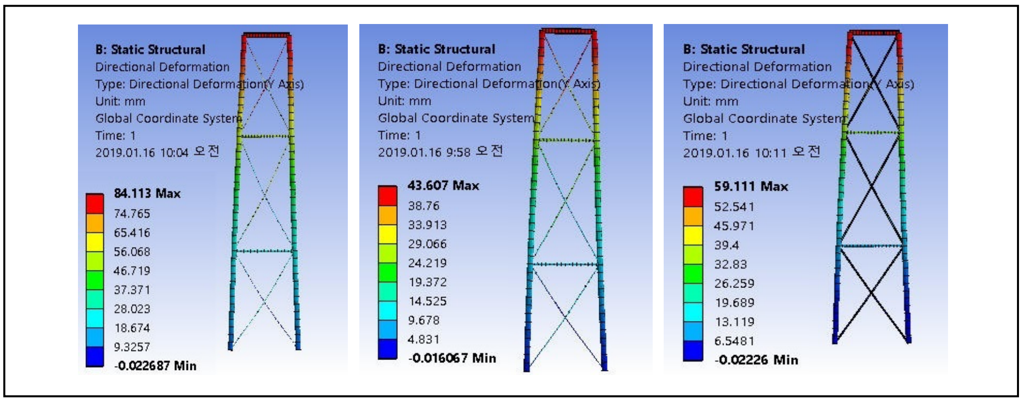

Figure 14 (c) The Case of The Pre-Stressed Brace (Reinforcing Bar- Φ19mm, Φ32mm, Angle Rolled-Steel Shape 75x5)

Summarizing the results is shown in table 4.

Table 4 EFFECT of Bracing on Stiffness of Support Structure (The Displacement of The Upper Part Under The 7 Tons of Centrifugal Force, mm)

Behavior of brace	**Φ**19mm	**Angle** 75x75x5x5	**Φ**32mm
Only in tension	98.2	31.4	59.3
In tension or compression	62.2	20.4	35.5
in pre-stress	90.1	24.3	50.6

4.2 Analysis modeling to determine the reasonable cross section of the brace

The optimization control parameters for simulation analysis are three; cross-sectional area of the braces, the brace behavior and the brace preload.

The cross section of the brace was chosen by a 19mm, 25mm of reinforcing bar, an Angle rolled-steel shape 75×5 bar and a 32mm reinforcing bar, respectively.

The first objective function is the strength and stiffness safety of the roller coaster car support structure.

The strength and stiffness safety factors of the support structures subjected to tensile, compressive and flexural fatigue should be more than 2.3,

$$\sigma_{\max} \le \frac{\sigma_u}{2.3} = 0.435\sigma_u$$

where σ_u is the ultimate stress.

The second objective function is to minimize the shock to the roller coaster car.

4.3 Optimize the cross-section of braces and determination the reasonable displacement value of support structure

A. nonlinear dynamic simulation

nonlinear dynamic simulation

The analysis model of the roller coaster car support structure is made like in figure 13 and analyzed.

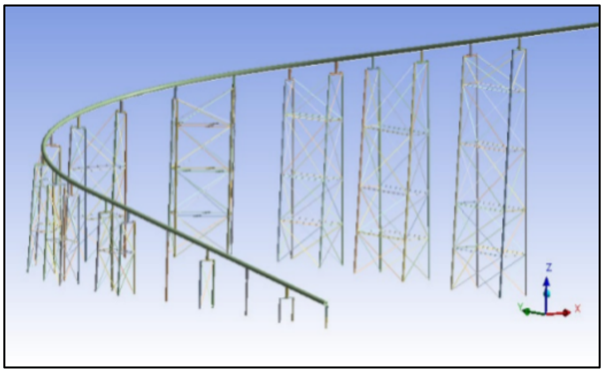

Figure 15 Analysis Model in ADAMS

The highest column in the starting line is 30m in height.

The first column to be calculated is column 13, which is 25.6m high.

Therefore, calculating the velocity in column 13, the following is:

$$v_o = \sqrt{2g\Delta h} = \sqrt{2\cdot 9.8\cdot (30-2.56)} = 9.287m/s$$

This velocity is decomposed into components with respected to the coordinates specified in the analysis model as follows (Figure 16).

$$v_{ox} = 0$$
$$v_{oy} = v_o \cdot \frac{8}{\sqrt{8^2 + (25.6-24.1)^2}} = 9.128m/s$$
$$v_{ox} = v_o \cdot \frac{(25.6-24.1)}{\sqrt{8^2 + (25.6-24.1)^2}} = 1.7115m/s$$

Here, v_{ox}, v_{oy}, v_{ox}- radial, horizontal and vertical components.

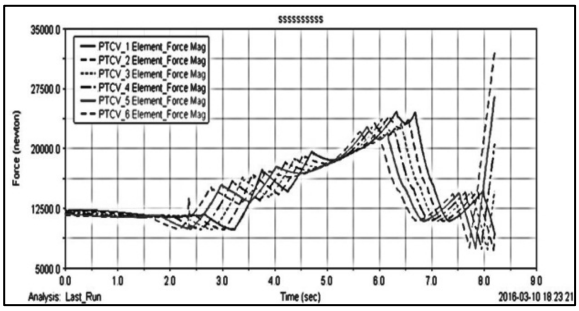

Figure 16 Load-Time Curve of Each Train of The Roller Coaster Car To The Track

The maximum displacements and stresses in a few columns of interest are as follows (Figure 17-18).

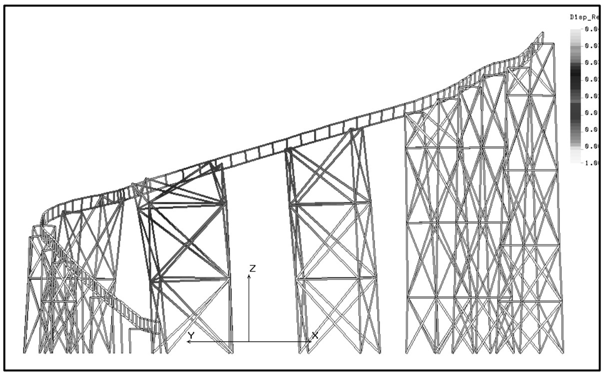

Figure 17 Analysis Result of Displacement at 5.3602s

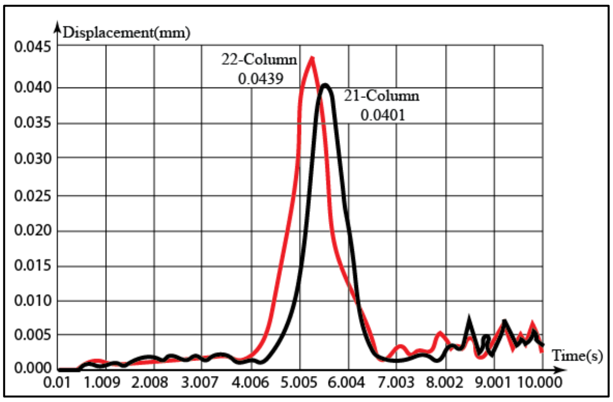

Figure 18 Displacement Response at Columns 21, 22

Summarizing the calculation results for the six cases available in practice, the following are summarized.

Table 5 Dynamic Simulation Results of 22- Column Support Structure

No	Type of the brace	Behavior of the brace	Maximum displacement (mm)	Maximum stress (MPa)	plan stiffness
1	Φ19mm	compression	39.2	151.7	1.625
2		no compression	72.2	290.5	0.941
3	Φ25mm	compression	21.3	92.2	2.223
4		no compression	33.15	166.6	1.352
5	Φ32mm	compression	33.7	56.0	2.786
6		no compression	43.9	112.8	1.793
7	Angle 75x75x5x5	compression	30.2	58.2	2.670
8		no compression	40.3	128.9	1.897

Analysis

Table 6 Safety Factor of Strength From Analysis Results

No	Case of cross-section type	Case of behavior	Maximum stress (MPa)	Safety factor of strength
1	Φ19mm	compression	151.7	1.713909
2		no compression	290.5	0.895009
3	Φ25mm	compression	92.2	2.819957
4		no compression	166.6	1.560624
5	Φ32mm	compression	56.0	4.642857
6		no compression	112.8	2.304965
7	Angle 75x75x5x5	compression	58.2	4.467354
8		no compression	128.9	2.017067

The case with the smallest stiffness with a safety factor of more than 2.3 is 1.793, in the case of 6, where Φ32mm brace do not work in compression (Table 5 and 6).

From the above analysis, it can be seen that using the Φ32mm reinforcing bar as a brace is the most reasonable.

B. Accuracy analysis of dynamic simulation

The mean acceleration is 1.371g when the radial horizontal displacement at the top of the 22 column is 50mm during operation, and upper-lower displacement difference of the support structural column is 3-4mm.

The radial maximum displacement at the top of 22-column obtained as a result of nonlinear dynamic analysis is 43.9mm (table 4-2).

Calculating the horizontal displacement of the support structure by considering the column displacement difference of 3-4mm is 3.5mm*13.2/4=11.6mm and 43.9+11.6=55.5mm.

Here: 3.5mm-upper and lower displacement difference of column

13.2m- height of column

4m- distance between the column bases

Therefore, the error rate is $\frac{55.5-50}{55.5}\times 100 = 9.9\ \%$

Hence, nonlinear dynamic analysis results reflect the current state of the track with accuracy 90.1% (Figure 19).

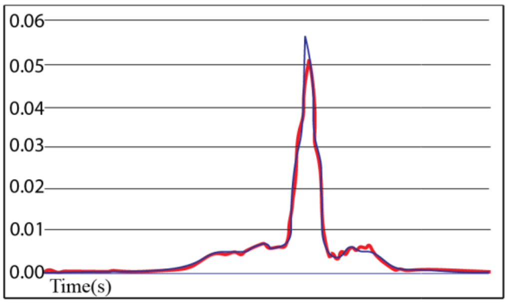

Figure 19 Result of Measurement and Simulation

C. Safety evaluation of the roller coaster car support structure

From the simulation results, the elastic limit and the ultimate stress were compared with maximum displacement and stress in 22-column (Table 7).

Table 7 Analysis Table in 22-Column

Maximum stress	112.8
Elastic limit	260
Safety factor	260/112.8≈2.305

Therefore, the optimal horizontal displacement value of the roller coaster car support structure is set to 50mm±5mm and the ductility control of the seasonal support structure is adopted.

5 Conclusion

The paper established the most reasonable analysis model, analysis method and ductility control method to ensure the strength and stiffness safety of the roller coaster car support structure, thus providing a guarantee for ensuring the safety of the operating roller coaster cars in our country.

REFERENCES

[1] Maureen Byko, "Materials give roller coaster enthusiasts a reason to scream," *JOM*, vol. 54, no. 5, p. 16, 2002.

[2] A Väisänen, "Design of roller coasters," 2018.

[3] Roh Hwasung and Andrei M Reinhorn, "Nonlinear static analysis of structures with rocking columns," *Journal of structural engineering*, vol. 136, no. 5, pp. 532-542, 2010.

[4] H Sohn, "Effects of environmental and operational variability on structural health monitoring," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 365, no. 1851, pp. 539-560, 2007.

[5] Der-Shen Yang and C. M. Wang, "Dynamic response and stability of an inclined Euler beam under a moving vertical concentrated load," *Engineering Structures*, vol. 186, pp. 243-254, 2019.

[6] Margarida Alves, Ann MacPhail, Paula Queirós, and Paula Batista, "Becoming a physical education teacher during formalised school placement: A rollercoaster of emotions," *European Physical Education Review*, vol. 25, no. 3, pp. 893-909, 2019.

[7] Roberta Riccelli et al., "Neuroticism modulates brain visuo-vestibular and anxiety systems during a virtual rollercoaster task," *Human Brain Mapping*, vol. 38, no. 2, pp. 715-726, 2017.

[8] Ge Ning Xu, Peng Xiao Liu, and Heng Yang, "Research on Anti-Seismic Analysis the Overall Structure of Three-Ring Roller Coaster Based on Response Spectrum Method," *In Advanced Materials Research*, vol. 712, no. Trans Tech Publications Ltd., pp. 1690-1694, 2013.

[9] Yoshio Fukuda, Maria Q. Feng, and Masanobu Shinozuka, "ost-effective vision-based system for monitoring dynamic response of civil engineering structures," *Structural Control and Health Monitoring*, vol. 17, no. 10, pp. 918-936, 2010.

[10] Piotr Kohut et al., "Monitoring of a civil structure's state based on noncontact measurements," *Structural Health Monitoring*, vol. 12, no. 5-6, pp. 411-429, 2013.

[11] Marcel Bastiaansen, Monique Oosterholt, Ondrej Mitas, Danny Han, and Xander Lub, "An emotional roller coaster: Electrophysiological evidence of emotional engagement during a roller-coaster ride with virtual reality add-on," *Journal of Hospitality & Tourism Research*, vol. 46, no. 1, pp. 29-54, 2022.

[12] C. Braccesi and F. Cianetti, "Development of a procedure for the structural design of roller coaster structures: The rails," *Engineering Structures*, vol. 93, pp. 13-26, 2015.

[13] Ferdinand P. Beer, E.Russell Johnston, Jr. John T. DeWolf, and David F. Mazurek, "MECHNICS OF MATERIALS," *Library of Congrees Cataloging –in-Publication*, pp. 57-72, A13-A22, 2015.

[14] NAKASONE Y. and YOSHIMOTO S., *ENGINEERING ANALYSIS with ANSYS* , 331451st ed. Tokyo, Japan: Department of Mechanical Engineering Tokyo University of Science, 2006.

[15] "General Structural Steel-Technical requirement," D.P.R.Korea, 2008.