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Damages Inspection and Finite Element Model Analysis of Static and Dynamic Factors of Steel Girder-Concrete Composite Span Due to Vehicles Live Load and Loads Combination

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ABSTRACT

This study's primary goals are to: Identify any damage that may have happened to the structural elements of steel I-girder-concrete composite spans; determine the static responses according to the influence of the vehicle and service loads (loads combination case) using numerical static analysis FEM using CSI-Bridge Ver. 25; measure the natural frequency of the bridge structure according to the influence of self-weight of the structure using modal analysis; determine the dynamic responses due to vehicle live load using numerical dynamic time history analysis by using Finite Element Method (FEM); assess the constructional effectiveness of bridge structures and identify methods for reinforcing and repairing damaged structural elements. Damage inspection results of steel I-girder span showed that the damage is not severe in the structural parts of span. Steel I-girders span shows no signs of rust or corrosion, but the main problem is in the expansion joints and they need to be repaired or replaced. Under the effect of vehicles live load and load combinations, maximum tensile stress appeared at the bottom of steel I-girder span, which was 13.56MPa and 86MPa respectively, lowering than the allowable value of tensile stresses from AASHTO LRFD BRIDGE, which is equal to 207MPa. The maximum deflection in the downward direction due to vehicles load and load combination was 10.9 mm and 91 mm, respectively. Meeting the allowable deflection values of 70 mm (live load) and 112 mm (loads combination). The Finite Element dynamic analysis described that the average value of vibration frequency is 6.42Hz. Compared with natural frequency, it is higher than 2.95Hz, indicating that the span of bridge will face vibration issues because this span has a long length. Therefore, this study recommended that to add more steel girders with more diaphragms (cross beams) to reduce the vibration of bridge span.

1. INTRODUCTION

A bridge consists of a set of components that are divided into two main sections, where the superstructure includes bearings, beams or girders, bridge deck, joints, paving layers, security barriers, and water disposal system, while the substructure includes foundations, columns, and column heads, while the substructure includes foundations, columns, and column heads. Bridges are built to cross barriers like rivers, roadways, and railroads. They are categorized either by the kind of materials used in their construction or by the kind of support that they utilize. Simple truss bridges and continuous bridges are included in the categorization by type of support, whereas concrete, prestressed concrete, wooden, and steel bridges are included in the classification by construction material [1-6].

A bridge is a man-made structure that crosses physical barriers, like a valley, a waterway, or a highway, without blocking traffic below. Bridge type selection is determined by site features, vendor choices, site hydraulics, profile placement, and construction expenses. The density and amount of traffic loads influence the dimensions of the bridge structure, which is essential for the region that the bridge links [7-11].

The evaluation of each bridge is crucial for gathering data regarding the structural state and sufficiency of the bridge. This data should be maintained as a permanent record of the bridge. Such documentation offers a valuable and precise historical account. It also includes information on past repairs, granting others easy access to relevant information. The aims of examining damages to the bridge elements are to assess whether the bridge structure is in a secure state, identify any essential upkeep, repairs, and fortification needed, create a foundation for funding any required maintenance and strengthening, and provide information to designers and construction engineers about aspects that need maintenance. Damage evaluation and maintenance of all bridge types are crucial for the safety of bridge users and are often tremendously significant for the local economy. Efficient bridge upkeep initiatives must be closely linked to the evaluation of the bridge parts. Hence, the maintenance department ought to comprise a permanent group of examiners referred to as the inspection team. The evaluation of the bridge encompasses all elements within the bridge to establish if it is in acceptable condition or requires repair or strengthening. The inspection strategy involves analyzing reports and conditions on-site, necessary Gears and equipment, vehicle flow management (as needed), site surveying, and constructional evaluations, which include assessing the Bridge surface, the components above the bearings, and the components under the bearing [12-20].

Superior strength and flexibility, a higher strength-to-cost ratio, and a lower strength-to-cost ratio in terms of compression as compared to concrete are just a few pros that steel frameworks have over other building materials. Steel bridges have more affordable foundations and lighter superstructures than concrete bridges. They can be made in portions in a facility with quality control measures in place. After that, these components are delivered to the location in manageable chunks and put together to create the entire bridge construction [21, 22].

Bridge designers' primary goal is to provide clients with affordable solutions that meet their objectives. By utilizing Concrete's compressive endurance in the slab and the tensile strength of steel in the primary girder, steel-concrete composite bridges offer a cost-effective solution for a range of span lengths. Shear connectors, which are welded to the upper flange of the steel girder and placed into the concrete slab, form the link between the steel and concrete elements of composite bridges. The longitudinal shear force that is conveyed through the shear connections enhances this composite action, markedly boosting bending resistance when compared to non-composite beams. Typically, composite indicates that the steel framework of a bridge is attached to the concrete structure of the deck, permitting the steel and concrete to operate together, thus lowering deflections and enhancing strength. This is achieved by using 'shear connectors,' which are secured to the steel beams and then incorporated into the concrete. Shear connectors may be welded on, potentially with the assistance of a 'stud welder', or, ideally in export projects, by utilizing nuts and bolts [23-26].

Constructed as concrete bridges because the superstructure constitutes a minor portion of the overall construction work for the primary contractor, who typically manages concrete foundations, piers, and abutments. The concepts of composite bridges encompass a span range of approximately 15m to 50m to connect the conventional span lengths of composite bridges-within that range, they address roughly 75% of all span requirements for road bridges. Simply supported structures are normally employed for single, short-span constructions. Multiple-span steel girder structures are engineered as continuous spans. When the total length of the continuous structure surpasses about 900', a transverse expansion joint is implemented using girder hinges and a modular watertight expansion device [27-32].

Bridge durability and strength are determined by materials used, system design, load nature, and environmental conditions. Vehicle weight has a significant impact on the structural integrity and safety of bridges. As cars drive across the bridge, dynamic parameters arise, such as vibration frequency, three-dimensional dynamic displacements, dynamic bending moments, dynamic shear pressures, and dynamic stresses and strains. These dynamic factors, which surpass static ones due to the interaction between moving cars and the bridge, can exacerbate the bridge's deterioration. The dynamic load applied by vehicles on the bridge can be affected by the dynamic characteristics of the vehicles, the dynamic properties of the bridge, the bridge's surface texture, and the speed of the vehicles. Although a gradual rise in dynamic load may not result in immediate failures of the bridge, these dynamic vehicle loads can cause damage that ultimately leads to long-term fatigue [33-37].

When bridge structures experience various forms of severe damage, stretching and repairing are necessary to restore the structural efficiency of the bridge. The enhancement of the bridge's constructional components can be pursued by changing substandard or damaged materials with superior quality materials, adding extra load-bearing components, and redistributing the loading effects through imposed deformations on the structural system. The choice of an appropriate technique for reinforcing and repairing the bridge's structural components relies on several factors. These factors include the type and age of the structure, the significance of the structure, the extent of strength that needs to be increased, the type and extent of harm, the resources available, cost, and workability, as well as aesthetics [38, 39].

This study's main goals are to: determine the structural parts of steel I-girder-concrete composite spans and identify any damage that has occurred in these components; evaluate the static responses under the influence of vehicle loads and service loads (load combination scenario) using numerical static analysis (FEM) using CSI-Bridge Ver. 25; determine the natural frequency of the bridge construction caused by its own weight using modal analysis; evaluate the dynamic responses resulting from vehicle live loads using numerical dynamic time history analysis (FEM); inspect the bridge framework's structural effectiveness and identify methods for reinforcing and repairing compromised structural elements.

2. METHODOLOGY OF STUDY

The methodology of this study includes selection of bridge structure, damage inspection of structural parts of steel span of bridge structure, numerical static analysis, and numerical dynamic analysis. Figure 1 explains the flow chart of methodology of study.

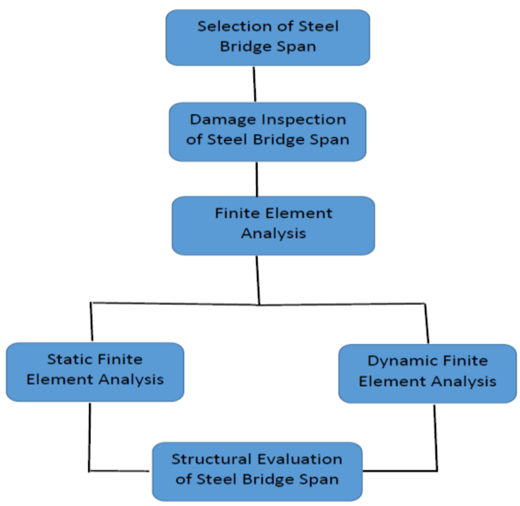


Figure 1. Methodology of study

3. STEEL I-GIRDER SPAN DESCRIPTION

In this study, Al-Thawra Bridge has been chosen to assess the structural performance because this bridge is significant due to its position in Babylon City in central Iraq. It is a composite bridge which is consists of I-steel girder span with eight precast prestressed concrete I-girders. This bridge was designed and constructed by Abdullah Owiz General Contracting Company and its construction began in 2010 as part of a strategic project aimed at alleviating traffic congestion at the entrance of Al-Hillah city and connecting Baghdad to the southern governorates. The bridge was designed with a total length of 488m and a width of 18.25 m, featuring Iraq's longest intermediate span of 56 meters. Originally planned for completion within 20 months, the bridge was successfully constructed in just 17 months due to favorable weather and dedicated engineering efforts. Originally planned for completion within 20 months, the bridge was successfully constructed in just 17 months due to favorable weather and dedicated engineering efforts. As mentioned above, it consists of nine spans. Eight of them are precast prestressed concrete I-girder section with 24 m length for each span and one of them is steel I-girder span, which has 56 m length. This study will select a steel-girder span to predict static and dynamic forces. This span has two bent supports. Each bent has three circular piers with 1.2 m diameter and 5 m height. Figure 2 shows the Al-Thawra bridge location, Figure 3 shows the Al-Thawra bridge structure, and Figure 4 shows the steel I-girder span layout and appearance.

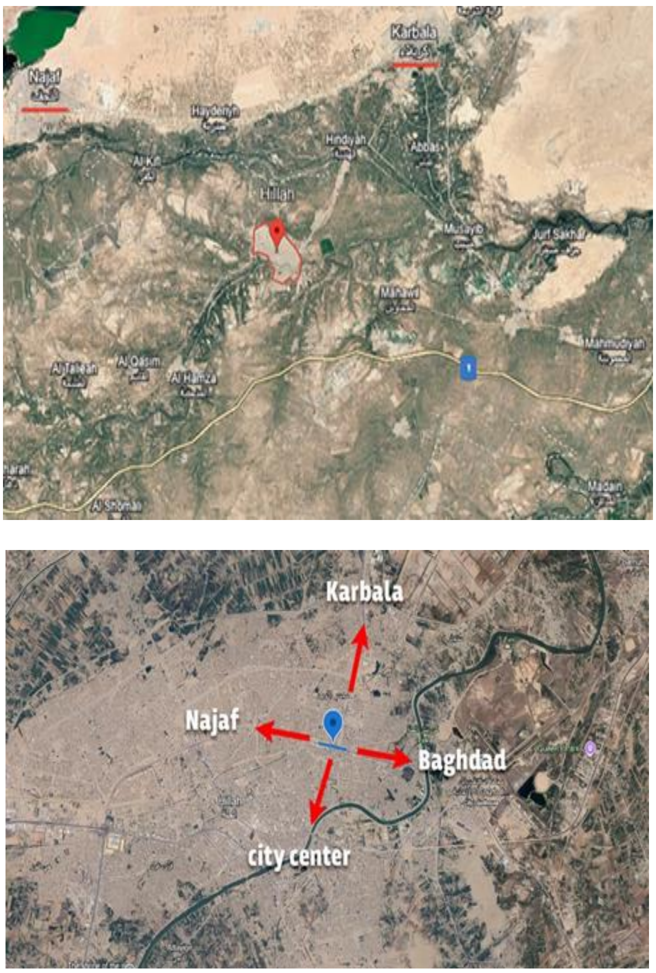
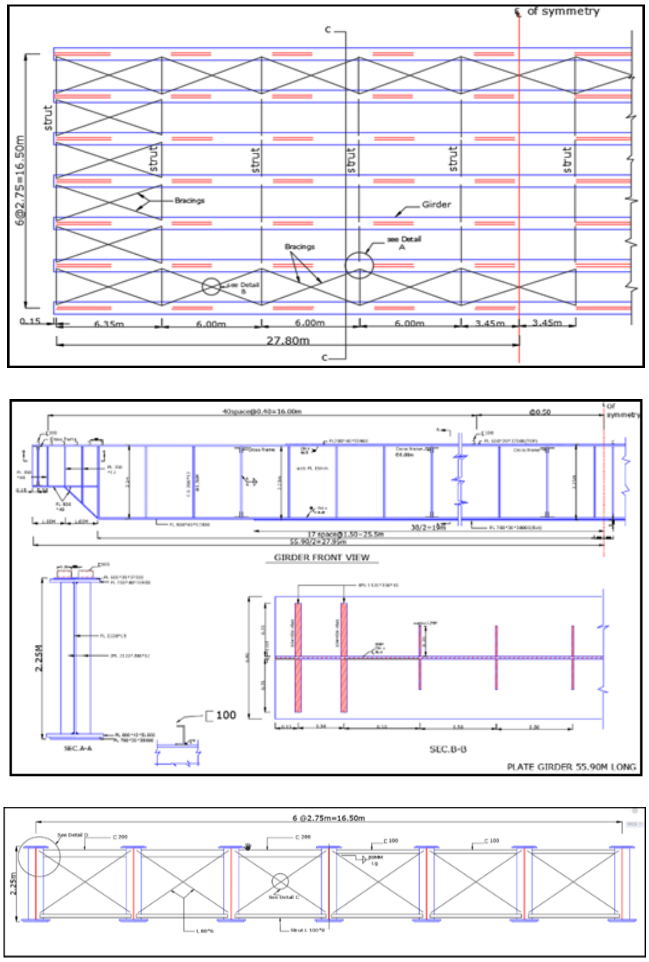


Figure 2. Location of the bridge in Babylon City

(a) Top view

(b) Side view

Figure 3. Al-Thawra bridge structure



(a) Layout of steel-girder span

(b) I-steel girder span appearance

Figure 4. Steel I-girder span layout and appearance

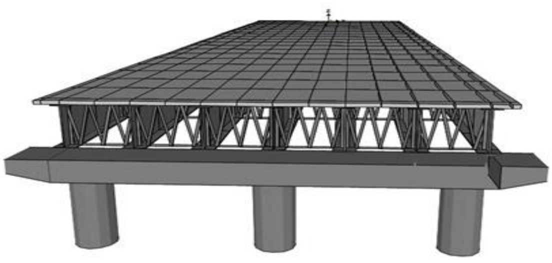
4. DAMAGES INSPECTION OF STEEL I-GIRDER SPAN

Damage inspection findings of the steel I-girder span indicated significant harm in the structural elements of the bridge. Steel I-girders span exhibit no indications of rust or corrosion. The obstruction must be cleared, and the rainfall drainage system must be repaired. It would also be wise to apply a moisture-resistant coating to the steel I-girders. It can be noted that from damage inspection, the main problem is in the expansion joints, which need to be repaired or replaced. Figure 5 shows the damage of expansion joints.

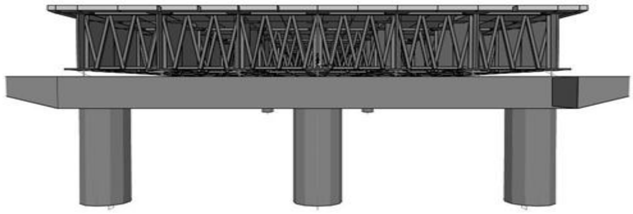
Figure 5. Damages of expansion joints

5. NUMERICAL MODELS OF STEEL I-GIRDER SPAN AND SERVICE LOADS

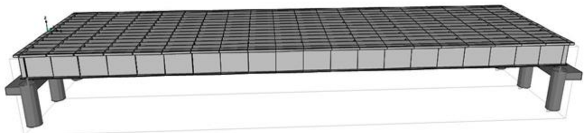
Numerical static and dynamic analysis of steel I-girder span is done by using CSI-Bridge Ver.25, which uses finite element analysis method. The type of area object model is shell element with maximum submish size is 1.2m. Maximum segment length of concrete deck, concrete piers and concrete pier caps is 3 m, respectively. The type of steel for girders is A709Gr50 with fy is 344MPa (50ksi). For concrete deck and substructure, the compressive strength is 50MPa. The bearing type is simply supported as hinge and roller. This study adopted two load cases. Vehicle traffic load case and loads combination case. Vehicles traffic load case represents the live load which uses vehicle in AASHTO type HS20-44. Load combinations comprise Permanent load, Pre-tensioned load, Dynamic vehicle load, temperature load, wearing surface, and wind load. Figure 6 shows the steel I-girder span model.



(a) Top view



(b) Front view



(c) Side view

Figure 6. Numerical model of steel I-girder span

6. FINITE ELEMENT ANALYSIS OF STATIC FACTORS UNDER VEHICLES LIVE LOAD

In this research, CSI-Bridge Ver. 25 is utilized to examine static reactions caused by vehicle live load in a static condition. These reactions consist of tensile stresses, compression stresses, and vertical deflection.

6.1 Steel I-Girder stresses

The findings of tensile and compression stresses resulting from static analysis under the influence of vehicles' live load for the upper and lower sections of steel I-girders are depicted in Figures 7 and 8. In Figure 7, the highest tensile stress at the top of the steel girders is 2.27MPa, which is below the permissible tensile stress value from (AASHTO LRFD BRIDGE), set at 207MPa. Regarding compression stress, the peak value at the top of the girders is -8. 61MPa, which is also beneath the allowable compression stress (207MPa). As illustrated in Figure 8, the highest tensile stresses occur at the center bottom of the steel girders, measuring 13.56MPa, while the greater bottom compression stress is -3.15MPa, both of which are under the allowable stress limit of 207MPa.

$$\sigma = 0.6 \times fyield$$

$$\sigma = 0.6 \times 345 = 207MPa\ (30ksi)$$ (for tensile and compression stress)

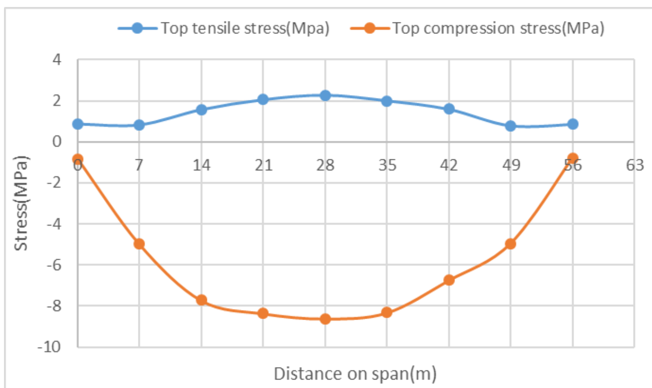


Figure 7. Tensile and compression stresses on top of steel girders due to vehicle live load case

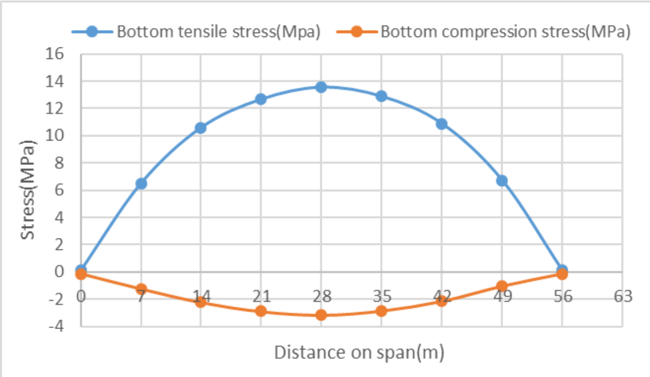


Figure 8. Tensile and compression stresses on bottom of steel girders due to vehicle live load

6.2 Vertical deflection

The highest vertical deflection in the downward direction is -10.9 mm, which is below the allowable limit value of 70 mm. Consequently, this value complies with the requirements in AASHTO LRFD. Figure 9 illustrates the vertical deflection values across the bridge spans. Figure 10 depicts the view of vertical deflection throughout the bridge spans.

$$allowable\ deflection = \frac{L}{800}$$

$$allowable\ deflection = \frac{56}{800} = 0.07m = 70mm$$

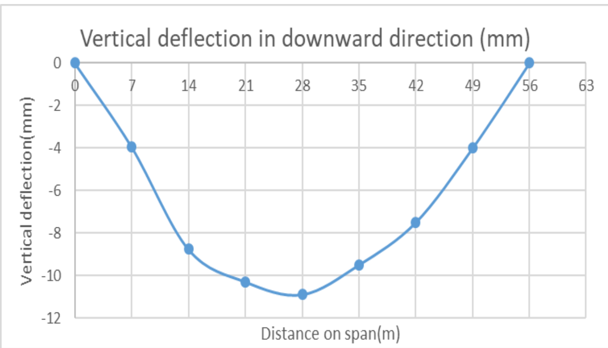


Figure 9. Vertical deflection in downward direction due to vehicle live load case along steel girders span length

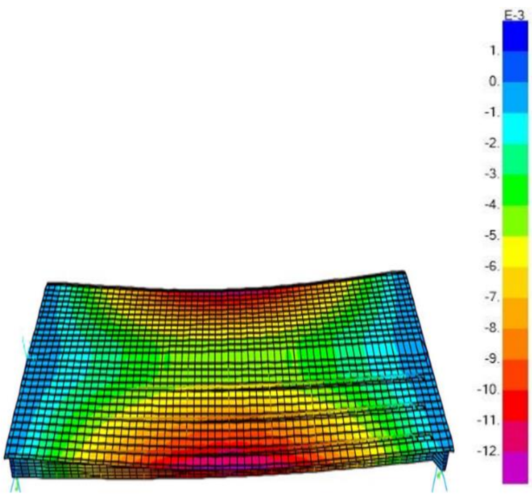


Figure 10. Viewing of vertical deflection in downward direction due to vehicle live load case

7. FINITE ELEMENT ANALYSIS OF STATIC FACTORS UNDER LOADS COMBINATION

7.1 Steel I-girder stresses

Pulling stresses do not appear at the top of steel girders, but they have compression stresses, and the higher value is -55MPa, which is lower than the allowable compression stress of 207MPa. Bottom of steel girder center has maximum value of tensile stress, which is 86MPa, less than allowable compression stress of 207MPa. This indicates that the bridge span has enough bearing capacity. Figure 11 shows Pulling and Crushing stresses on top of steel girders due to loads combination case along the span length, and Figure 12 shows tensile and compression stresses on the bottom of steel girders due to loads combination case along the span length.

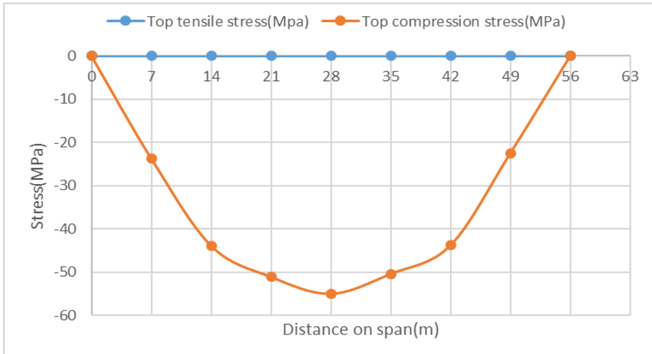


Figure 11. The tensile and compression stresses on top of steel girders due to loads combination case along bridge spans length

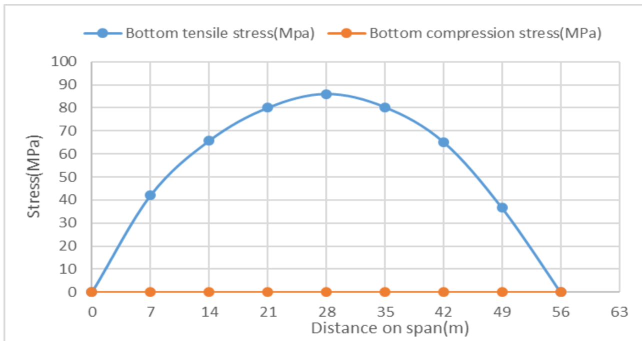


Figure 12. The tensile and compression stresses on bottom of steel girders due to loads combination case along bridge spans length

7.2 Vertical deflection

The values of vertical deflection along the steel girder span are displayed in Figures 13 and 14, with the greatest value under the combined action of loads being 91 mm downward. This figure shows that the steel bridge span can withstand loads and has sufficient stiffness in a static state because it is less than the permitted vertical deflection of 112 mm.

$$allowable\ deflection = \frac{L}{500}$$

$$allowable\ deflection = \frac{56}{500} = 0.112m = 112mm$$

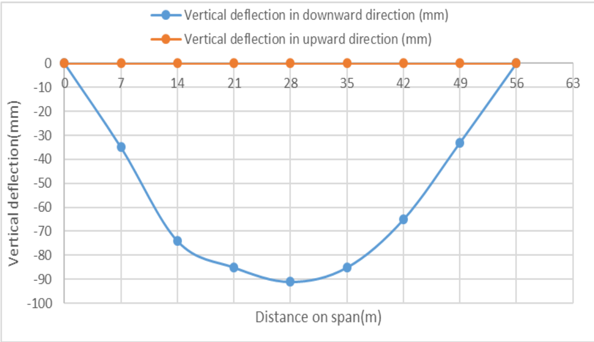


Figure 13. Vertical deflection in the downward direction due to loads combination case along steel girder span length

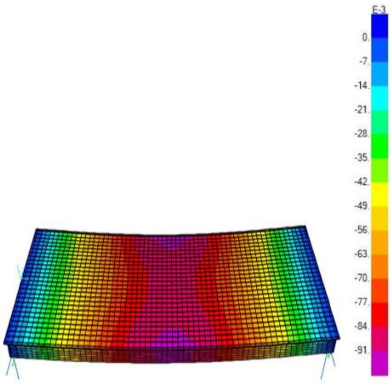


Figure 14. Viewing of vertical deflection in downward direction due to loads combination case along steel girder span length

8. FINITE ELEMENT ANALYSIS OF DYNAMIC FACTORS FOR STEEL SPAN MODEL UNDER VEHICLES LIVE LOAD

There are three dynamic factors are analyzed and determined in this study under design loads to assess the dynamic structural factors of steel girders span under effect of vehicles live loads with constant speed of 100 km/hr. These factors include natural vibration frequency, vehicles vibration frequency, vehicles dynamic displacement. CSI-Bridge Ver. 25 is used in the dynamic analysis by adopting time-history method.

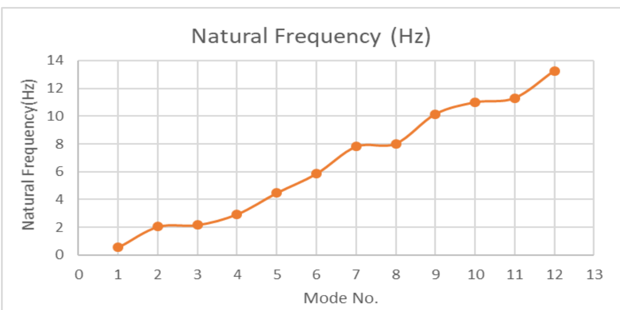


Figure 15. Natural frequency values with mode number for steel I-girder bridge span

8.1 Natural frequency magnitudes and modes shape of modal analysis

Mode No. 4's natural frequency of 2.95Hz was chosen because it reflects the typical downward deflection shape of steel girder spans under the influence of the structure's self-weight load. The natural frequency values and mode number for the steel I-girder bridge span are displayed in Figure 15. The link between time and mode number is depicted in Figure 16. The relation between time and natural frequency is depicted in Figure 17. The results of a modal analysis for a steel I-girder bridge span under the influence of the structure's self-weight are displayed in Figure 18.

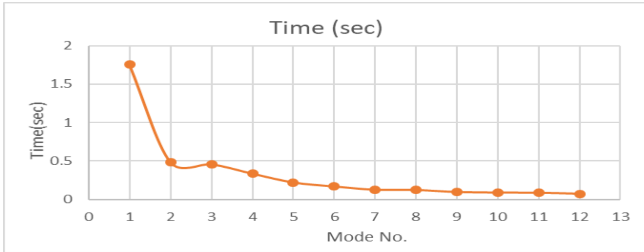


Figure 16. The relationship between time and mode number for steel I-girder bridge span

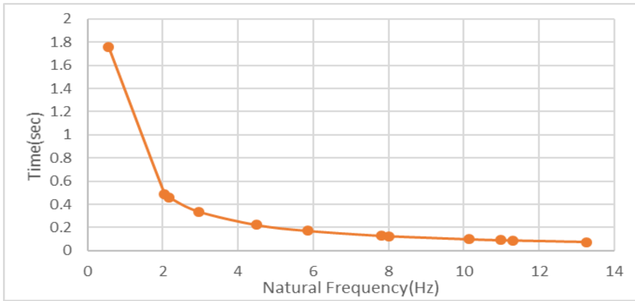
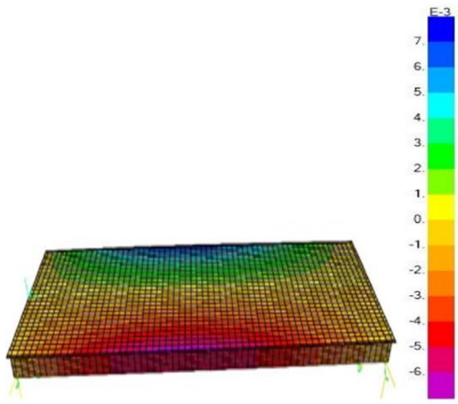
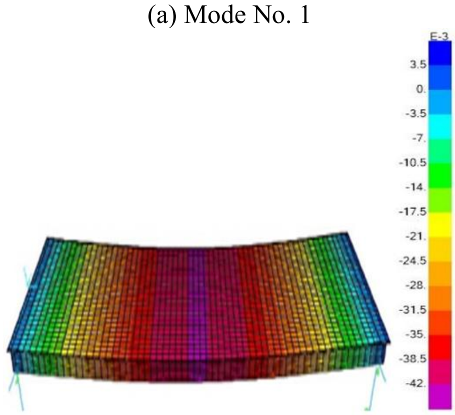


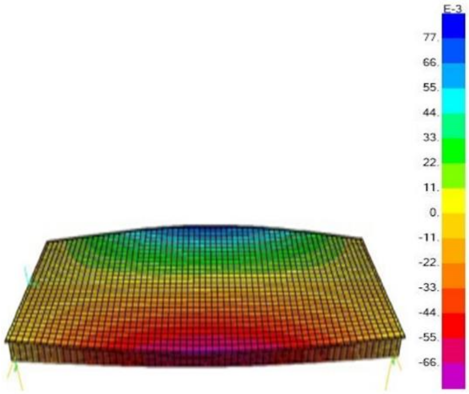
Figure 17. The relationship between natural frequency and time for steel I-girder bridge span



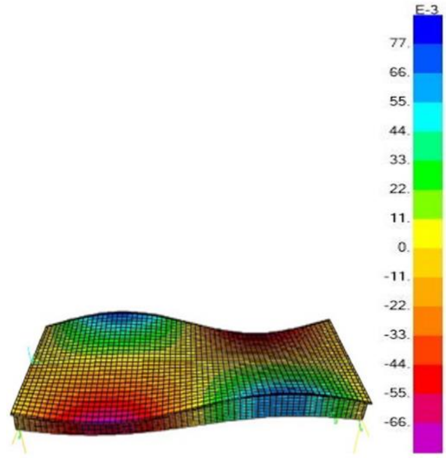
(a) Mode No. 1



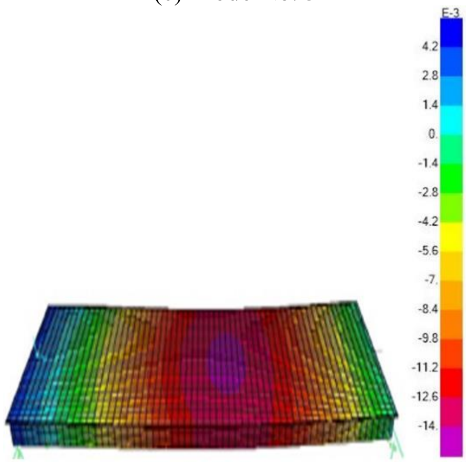
(b) Mode No. 2



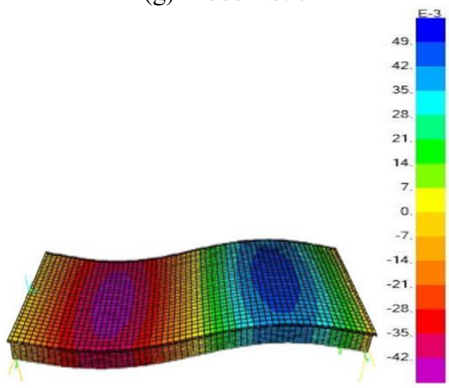
(c) Mode No. 3



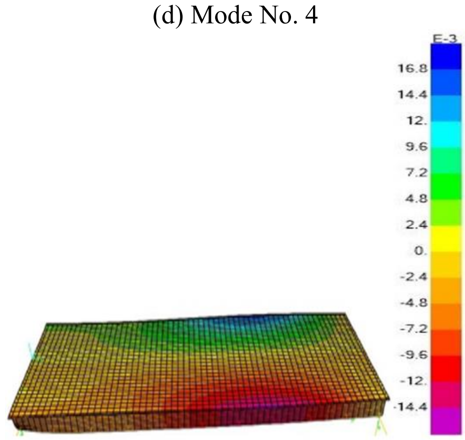
(g) Mode No. 7



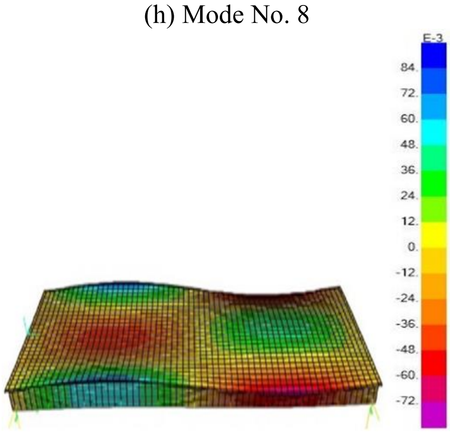
(d) Mode No. 4



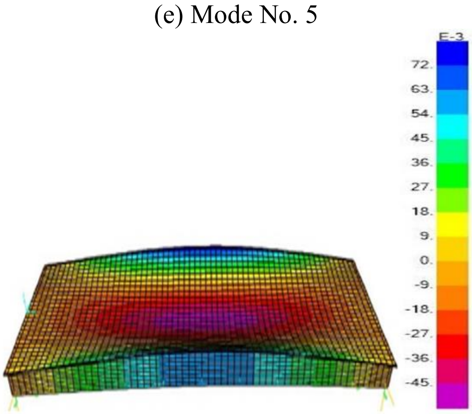
(h) Mode No. 8



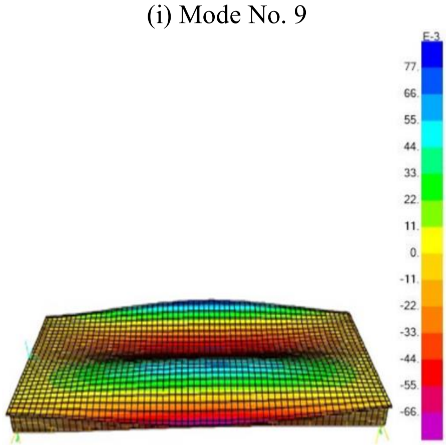
(e) Mode No. 5



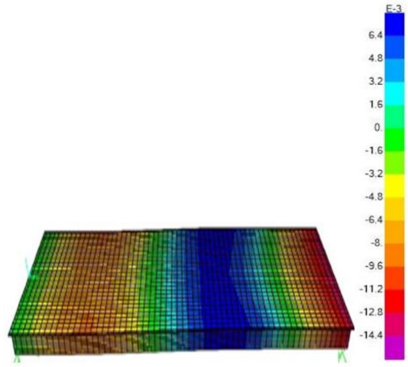
(i) Mode No. 9



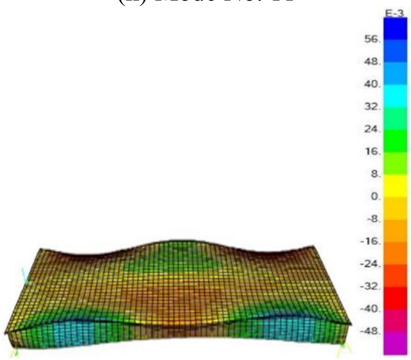
(f) Mode No. 6



(j) Mode No. 10



(k) Mode No. 11



(l) Mode No. 12

Figure 18. Modal analysis results for steel I-girder bridge span under effect of self-weight of structure

8.2 Vehicles vibration frequency

Time history analysis outcomes can be displayed in Tables 1 and 2. The mean value of vibration frequency is 7.83Hz. In comparison with natural frequency, it exceeds 2.95Hz, suggesting that the bridge span will experience vibration effects due to its long length, and it is necessary to incorporate additional steel girders along with more diaphragms (cross beams) to mitigate the vibration of the bridge span. Figure 19 illustrates the correlation between dynamic vibration frequency and longitudinal distance on bridge steel span.

Table 1. The values of dynamic vibration frequency for steel I-girder span under effect of vehicle live load

Longitudinal Distance on Spans (m)	Transverse Distance of Spans (m)	Joint No.	Dynamic Vibration Frequency (Hz)
3	+4	92	8
3	8	95	8
3	-4	98	8
14	+4	263	8
14	8	267	8
14	-4	271	8
25	+4	436	7.5
25	8	439	7.5
25	-4	442	7.5
36	+4	608	8
36	8	611	7.5
36	-4	614	8
42	+4	693	8
42	8	697	8
42	-4	701	8
53	+4	866	7.5
53	8	870	8
53	-4	872	7.5
Average			**7.83**

Table 2. Average values of dynamic vibration frequency for steel I-girder span under effect of vehicle live load

Longitudinal Distance on Spans (m)	Average values of Dynamic Vibration Frequency (Hz)
3	8
14	8
25	7.5
36	7.83
42	8
53	7.83

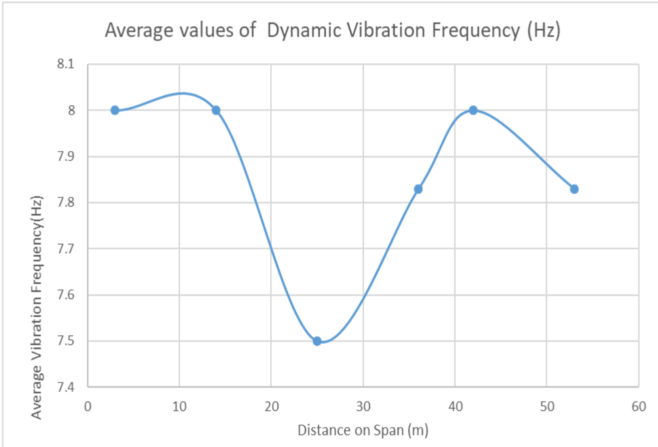


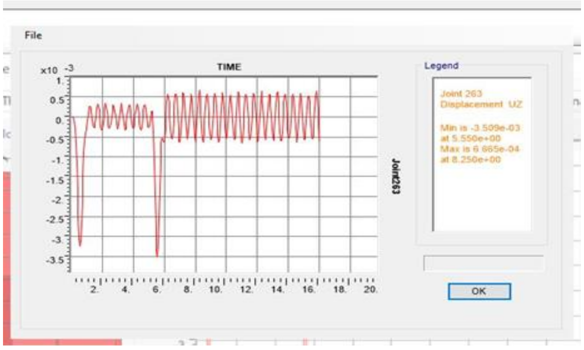
Figure 19. The correlation between dynamic vibration frequency and longitudinal distance on bridge steel span

8.3 Dynamic displacement due to vehicle load

Table 3 and Figure 20 display the findings of dynamic displacement while accommodating the traffic load. It is observed that the greatest upward vertical dynamic displacement value is 0.98 mm at the center of the steel girder span, while the lowest value is 0.58 mm at a distance of 14m from the starting point of the span. Regarding downward vertical deflection, the highest value occurs at the center of the span, which is -5.96 mm, and the lowest value is -3.40 mm.

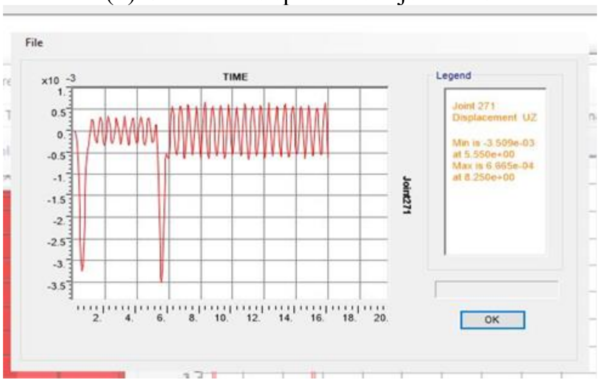
Table 3. The values of dynamic displacement for steel I-girder span under effect of vehicle live load

Longitudinal Distance on Spans (m)	Transverse Distance of Spans (m)	Joint No.	Downward Dynamic Displacement (mm)	Upward Dynamic Displacement (mm)
14	+4	263	-3.50	0.66
14	8	267	-4.11	0.58
14	- 4	271	-3.50	0.66
21	+4	380	-4.76	0.87
21	8	384	-5.70	0.93
21	- 4	388	-4.76	0.88
28	+4	466	-4.90	0.93
28	8	470	**-5.96**	**0.98**
28	- 4	474	-4.90	0.93
42	+4	693	-3.40	0.67
42	8	697	-3.80	0.73
42	- 4	701	-3.40	0.67

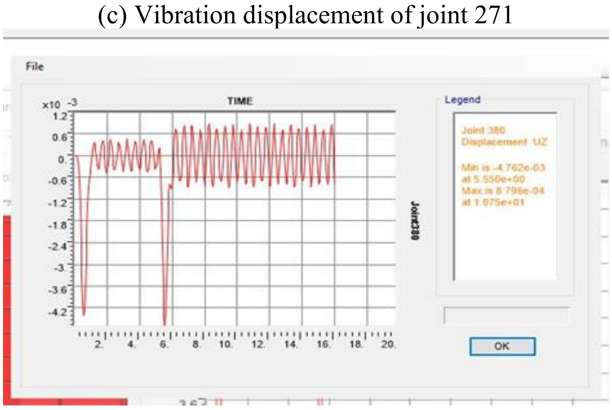


(a) Vibration displacement of joint 263

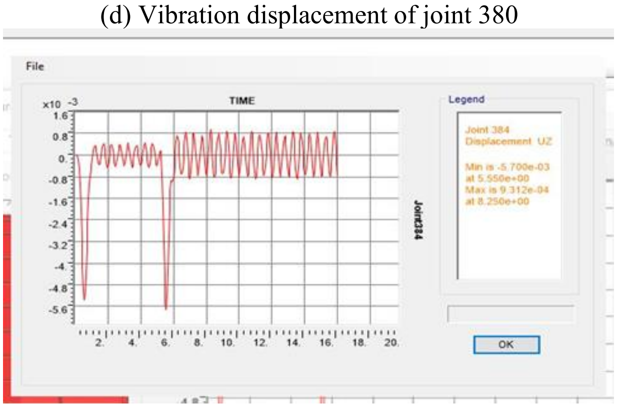
(b) Vibration displacement joint 267



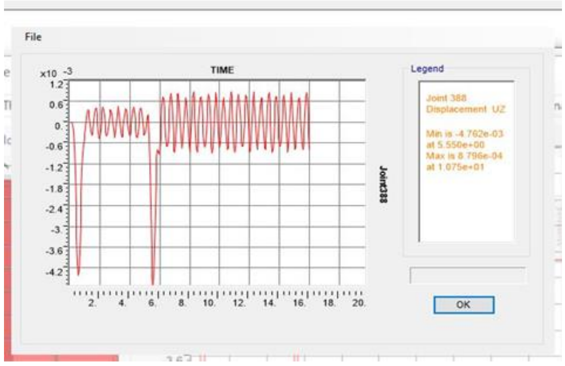
(c) Vibration displacement of joint 271



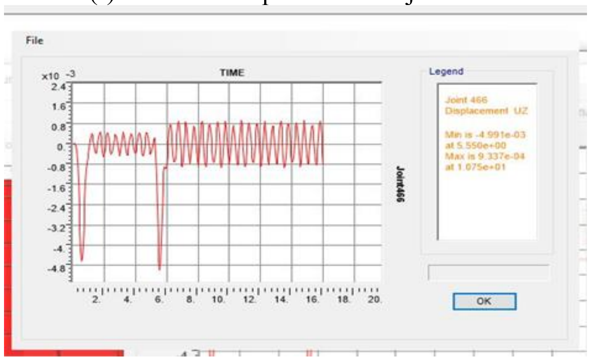
(d) Vibration displacement of joint 380



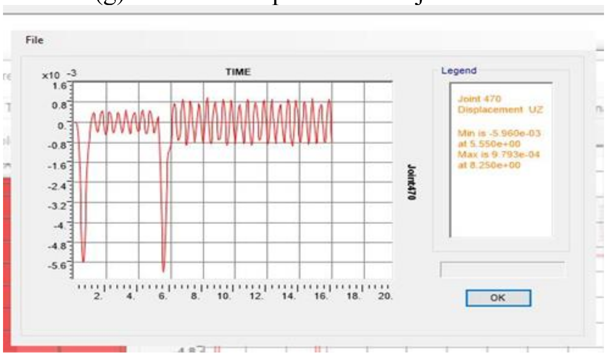
(e) Vibration displacement of joint 384



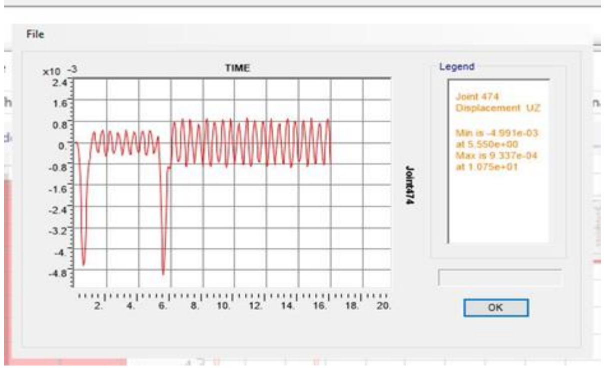
(f) Vibration displacement of joint 388



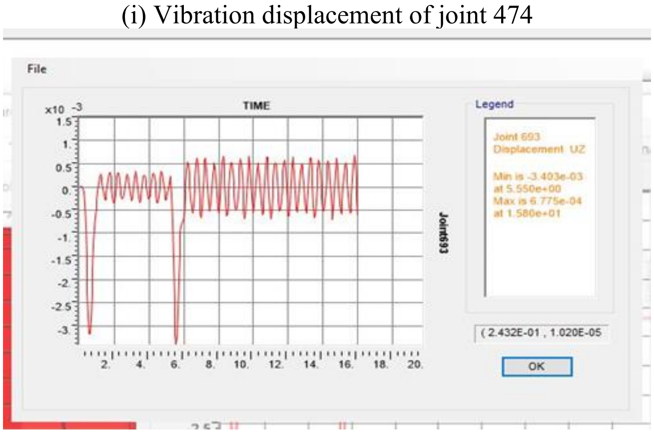
(g) Vibration displacement of joint 466



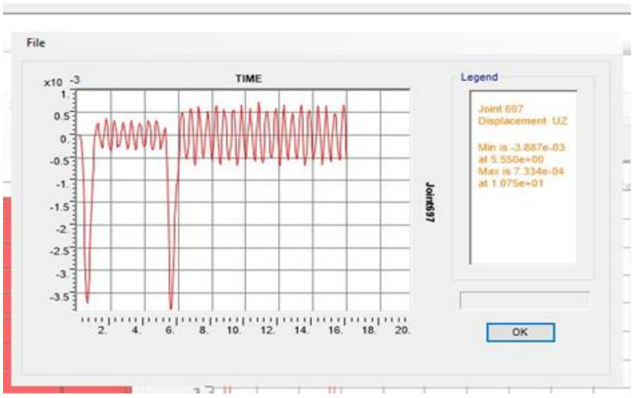
(h) Vibration displacement of joint 470



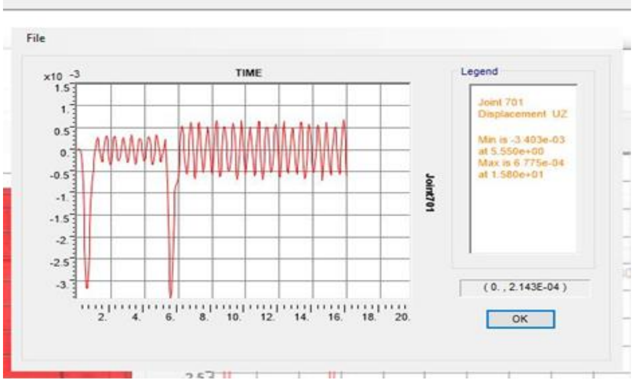
(i) Vibration displacement of joint 474



(j) Vibration displacement of joint 693



(k) Vibration displacement of joint 697



(l) Vibration displacement of joint 701

Figure 20. Curves of CSI-bridge for dynamic displacement for steel I-girder span under effect of vehicle live load

9. STRUCTURAL EVALUATION OF STEEL SPAN OF THE BRIDGE

According to damage inspection and finite element analysis of static responses, the results showed that the structural performance of steel span parts is good and has enough stiffness and bearing capacity. Therefore, the bridge span doesn't need to be repaired or strengthened due to static loads. The results of dynamic responses explain that the bridge span has long vibration along the span length. Therefore, this study suggests adding more steel girders along with additional diaphragms (cross steel beams) to diminish the bridge span's vibrations.

10. CONCLUSIONS

The primary findings of this research are:

(1) The damage evaluation results of the steel I-girder span indicated that there are no significant damages in the structural components of the span. Steel I-girders span displays no indications of rust or corrosion. The obstruction needs to be eliminated, and the rainfall drainage system requires repair. Additionally, it would be prudent to apply a moisture-resistant coating to the steel I-girders. It can also be observed that the damage inspection revealed that the primary concern lies within the expansion joints, which require either repair or replacement.

(2) The results of the finite element static analysis under vehicular load revealed that the maximum tensile stress at the top of the steel girders is 2.27MPa, which is below the permissible tensile stress value as per AASHTO LRFD BRIDGE standards, set at 207MPa. Regarding compression stress, the maximum value found at the top of the girders is -8.61MPa, which is also below the allowable compression stress (207MPa). The maximum tensile stresses are located at the bottom center of the steel girders, measuring 13.56MPa, while the higher bottom compression stress is -3.15, both lower than the allowable stresses of 207MPa. The greatest downward vertical deflection measured is -10. 9mm, which is below the permissible limit of 70mm. Therefore, this value complies with AASHTO LRFD requirements.

(3) The load combination analysis results indicated that tensile stresses do not appear at the top of the steel girders; however, they do experience compression stresses, with the highest value being -55MPa, which is beneath the allowable compression stress of 207MPa. The maximum tensile stress value at the center of the bottom of the steel girder is 86MPa, which is less than the allowable compression stress of 207MPa, indicating that the bridge span possesses adequate bearing capacity. The maximum value resulting from the load combination effect is 91 mm downward, which is below the permissible vertical deflection of 112 mm, suggesting that the steel bridge span can withstand loads and has sufficient stiffness in a static state.

(4) The finite element dynamic analysis indicated that the average frequency of vibration is 6.42Hz. When compared with the natural frequency of 2.95Hz, it is higher, suggesting that the bridge span will experience vibration due to its long length, necessitating the addition of more steel girders along with additional diaphragms (cross beams) to diminish the bridge span's vibrations. The dynamic displacement analysis results revealed that the bridge span displaced downward more than upward. The maximum upward vertical dynamic displacement is recorded at 0.98 mm at the center of the steel girder span, while the minimum is 0.58 mm at a distance of 14 m from the beginning of the span. For downward vertical deflection, the highest value recorded was at the center of the span, showing -5.96 mm, and the lowest value measured was -3.40 mm.

(5) The methodology of this study can be applied to evaluate the structural performance of new and old constructed bridges and can be used with other methods and tests of evaluation, such as static load tests and dynamic load tests, use other engineering software in the application of finite element analysis.

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