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Improving Deck Displacement and Stiffness of a Field-Measured Bridge by Effect of Load Distribution Factors between Girders

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Abstract

A field investigation is conducted to strengthening of Karkhe Bridge with type of steel slab-on-girder in Khouzestan, Iran that it was damaged due to unusual loading and had been extra vibration. In the first, two types of truck are assigned that one of them has loading of Iranian code (40-ton-truck), and other has unusual loading (90-ton-truck) that used in field for transportation of materials. In the next step, this bridge is analyzed by finite element method under these two types of loading, and load distribution factors for different modes are determined. According to these factors, flexural and torsional moment and also displacements of bridge are calculated. In order to strengthening of bridge, fin sections are used to increasing the flexural stiffness for girders, and lateral bracings are used to increasing the torsional stiffness. Finally, results of analysis after strengthening of structure are compared with results before strengthening, that it shows improving in distribution of load between girders and decrease of displacements for bridge deck.

Keywords: Steel Bridge, Slab-on-girder, Torsional stiffness, Unusual load, Finite element method,

1. Introduction

The steel slab-on-girder bridge of Karkhe is created with three 60-meter-spans and one 25-meter-span. This bridge is constructed for transportation of vehicles and devices to dam workshop beyond the valley. The design of this bridge is according to the AASHTO conditions [1], but the loading is based on specifications of Iran's 40-ton-truck [2], and also the materials are selected by these conditions.

In the operation process, according to the high earthworks volume in project, special vehicles such as 90-ton-vehicle is used. So, this heavy amount of load by this truck is unusual for the bridge. Although, in design process, the specifications of this truck was not considered and constructed sections was weak for this loading. As a result, high vibrations and deflections are produced at bridge during the transportation, and using bridge was impossible.

In this research, a solution for recovering and reinforcing this bridge that is based on investigations and studies is considered. In this regard, three methods are developed as follows: increase in torsional stiffness of girders to balance the forces, increase in flexural stiffness of girders for carrying highest forces and controlling the displacements.

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The research shows that increase in torsional stiffness according to relationship between flexural and torsional stiffness by orthotropic method is possible. As a matter of fact, abounding of AASHTO method is justified.

2. Structural Specifications of Bridge

Fig. 1 gives information of bridge. The bridge has 25-meter-span with 5 girders in height of 1.5 *m*. A concrete slab with 20 *cm* thickness is located on girders. Lane width of bridge is 10 *m*, and 1.25-meter-consul is considered from all sides of bridge that end of girders is leaned on adjacent bents. For using finite element method and investigating the structural behavior, specifications of girders and deck are elaborated as follows.

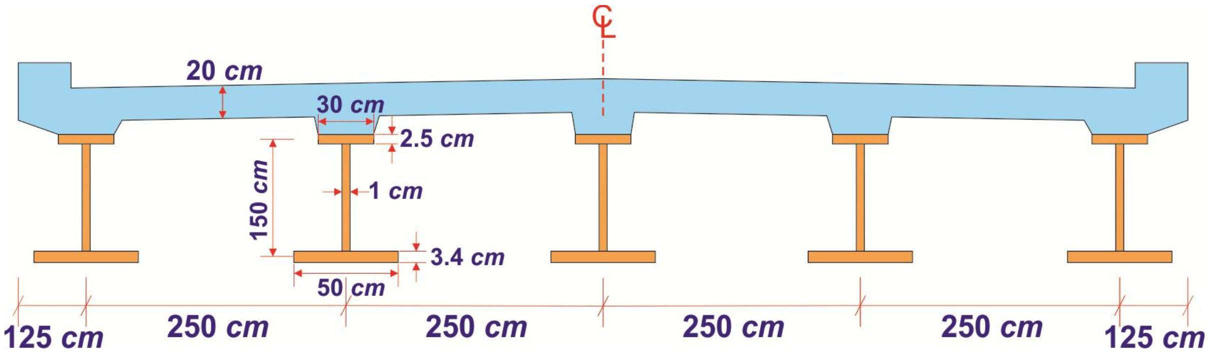

Figure 1. Transvers section of bridge with span length of 25 *m*.

Fig. 2 illustrates the structural analysis model in FEM. In order to analyzing the bridge, CSiBridge software [3] is considered. The sections of bridge such as 25-meter-span with 5 girders and abutments are modeled in the software. The 3D axes are assigned in the center line of structure. Concrete deck section type is Shell (Shell-thin) component, girder section type is Frame component, and abutment section is modeled by Spring component.

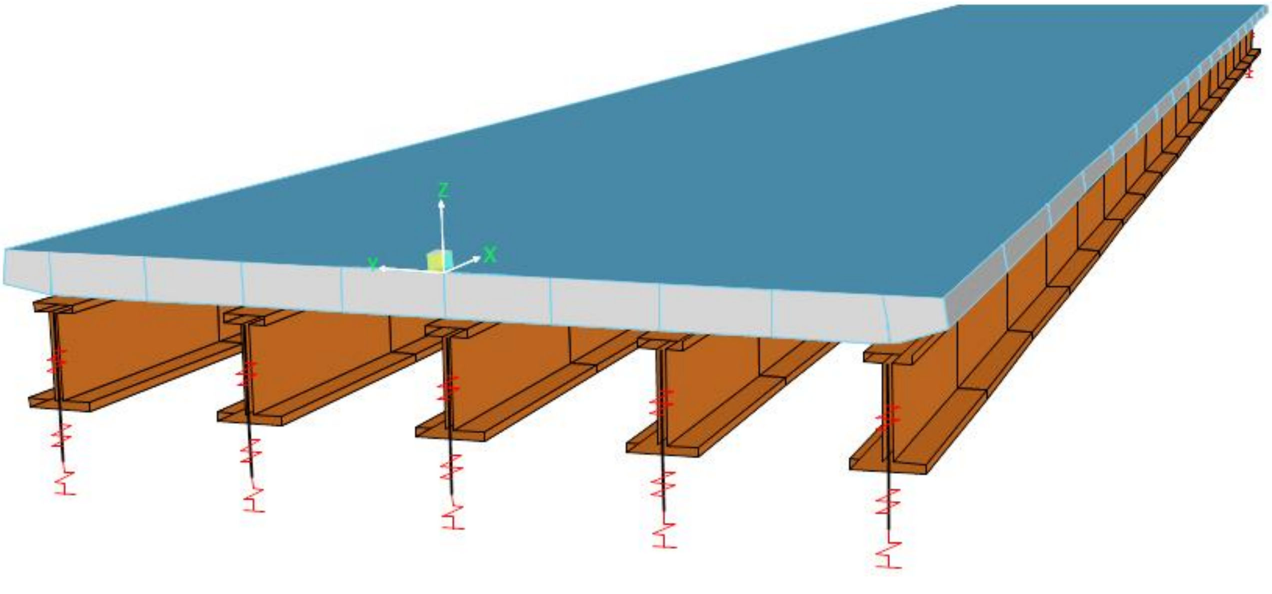

Figure 2. 3D structural analysis model of bridge that created by CSiBridge software.

3. Required Specifications of Bridge in Structural Analysis

Used parameters in finite element method according to Fig. 3 are as follows:

$$f_c' = 350\frac{kg}{cm^2} \Rightarrow \left\{n_{(AASHTO)} = 6\,, n_{(AISC)} = \frac{135}{\sqrt{f_c'}} = 7.5\right\} \Rightarrow n = 7.5$$

$$E_c = 2.8 \times 10^5 \frac{kg}{cm^2}\,, \qquad E_s = nE_c = 2.1 \times 10^6 \frac{kg}{cm^2}$$

$$V_s = 0.3\,, \qquad V_c = 0.15, \qquad G_s = 0.808 \times 10^6 \frac{kg}{cm^2}\,, \qquad G_c = 0.122 \times 10^6 \frac{kg}{cm^2}$$

$$t = 20\ cm\,, \qquad L = 2500\ cm\,, \qquad S_{Span} = 250\ cm$$

$$b_{e(AASHTO)} = \min\left\{\frac{L}{4}\,, S\,, 12t_{min}\right\} = \{625\,, 250\,, 240\} = 240\ cm\,, b_{effect} = \frac{b_e}{n} = 32\ cm$$

$$\bar{y} = \frac{30 \times 2.5 \times 150 + 32 \times 20 \times 160 + \frac{150^2}{2}}{50 \times 3.4 + 30 \times 2.5 + 32 \times 20 + 150 \times 1} = 120.7\ cm$$

$$I_G = \sum\left(\frac{bt^3}{12} + Ad^2\right) = 4.146 \times 10^6\ cm^4\ \,, J_G = \sum\left(\frac{bt^3}{3}\right) = 86.195 \times 10^3\ cm^4$$

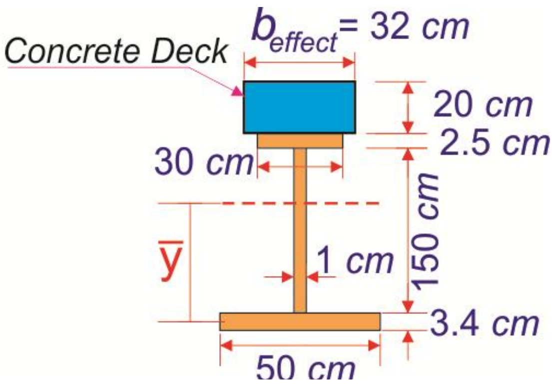

Figure 3. Dimensions of girder with converted concrete section.

4. Loading

4.1. Dead load

According to the thickness of concrete slab and implemented asphalt on it, the calculations are as follows:

Weight of Concrete= $0.2 \times 2.4 = 0.48\ \frac{ton}{m^2}$,

Weight of Asphalt in 4 *cm* thickness= $0.04 \times 2.2 = 0.088\ \frac{ton}{m^2}$

Dead load of the deck $= 0.48 + 0.088 = 0.568\ \frac{ton}{m^2}$

Portion of each girder of dead load for deck= $0.568 \times 2.5 = 1.42\ \frac{ton}{m}$

Weight of I-Girders= $[0.5 \times 0.034 + 0.15 \times 0.01 + 0.2 \times 0.025] \times 7.8 = 0.289\ \frac{ton}{m}$

Finally, moment of dead load calculates according to accumulate these weights with consuls, fencings and diaphragms weight:

$$D.L. = 2.2\ \frac{ton}{m} \Rightarrow M_{(D.L.)} = \frac{qL^2}{8} = 171.88\ ton.m$$

4.2. Live load

The loading of Iran’s 40-ton-truck and 90-ton-truck is stated as follows:

4.2.1 Iran's 40-ton-truck

The conditions of loading are according to AASHTO [1]. Fig. 4 gives the specifications of 40-ton-truck [2], and illustration of different modes of loading is shown in Fig. 5. According to 10-meter-width of lane and AASHTO, 3 lanes are considered for this truck. Besides, in order to getting maximum moment, position of truck along the longitudinal of bridge is considered according to influence line.

5 modes of loading is investigated that difference of them is in number and location of trucks at width of bridge deck.

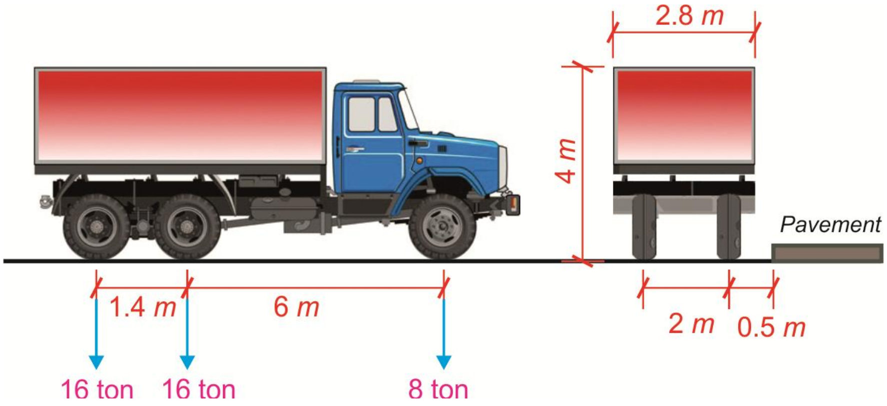

Figure 4. Specifications of 40-ton-truck.

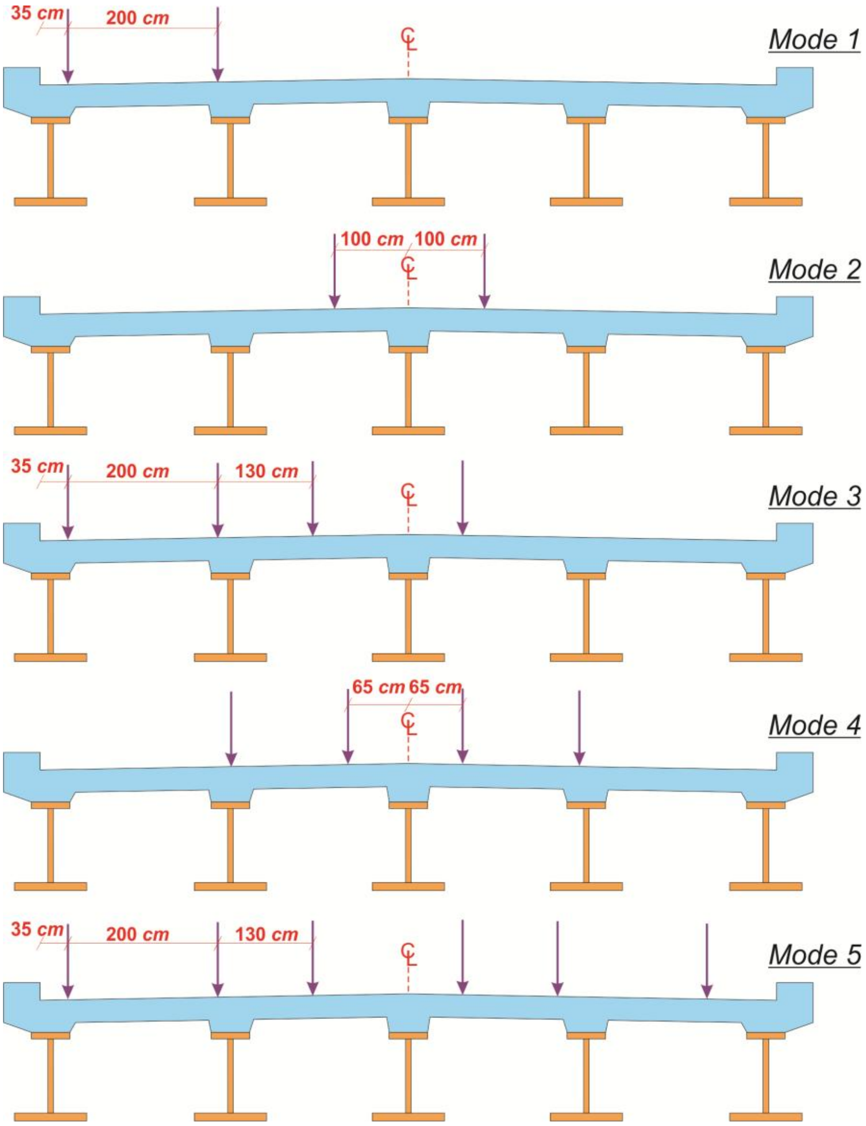

Figure 5. Modes of locating the position of 40-ton-truck in width of bridge.

4.2.2 Iran's 90-ton-truck

Fig. 6 illustrates the specifications of this truck that they are distance of axis, distance and number of wheels and loading ratio of wheels. In Fig. 7, according to high axis distance of truck, 4 modes of loading are shown. These modes are position order of truck in length of bridge for distributing maximum moment.

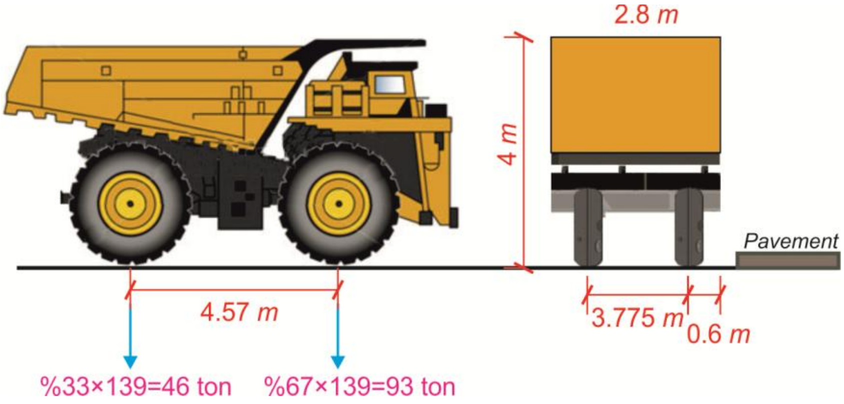

Figure 6. Specifications of 90-ton-truck.

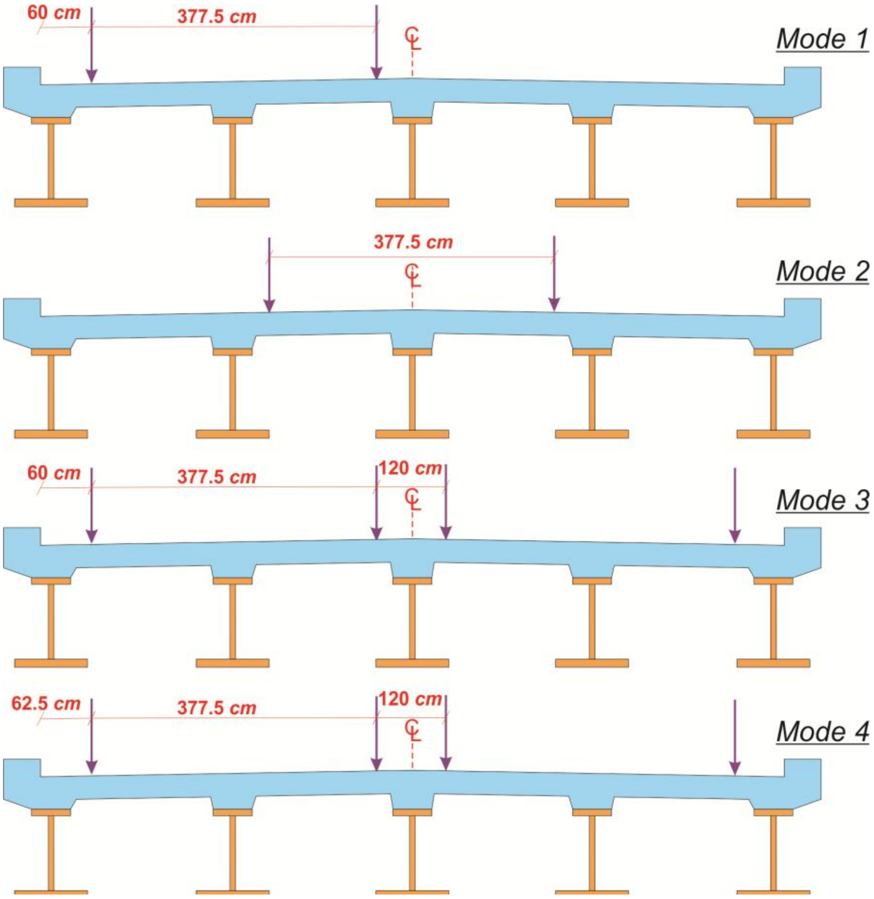

Figure 7. Modes of locating the position of 90-ton-truck in the width of bridge.

5. Analysis Results of Bridge for two Types of Loading

Table 1: Load distribution factors of 40-ton-truck between girders

	Mode				
Girder Number	1	2	3	4	5
1	0.990	0.105	1.144	0.372	1.076
2	0.694	0.535	1.271	0.995	1.402
3	0.335	0.720	1.051	1.267	1.509
4	0.054	0.535	0.542	0.995	1.260
5	-0.072	0.105	-0.009	0.372	0.753
Sum of Factors	2.0	2.0	4.0	4.0	6.0

Table 2: Load distribution factors of 90-ton-truck between girders

	Mode				
Girder Number	1	2	3	4	5
1	0.703	0.186	0.702	0.665	---
2	0.647	0.495	0.942	0.866	---
3	0.466	0.638	1.004	0.930	---
4	0.217	0.495	0.847	0.866	---
5	-0.033	0.186	0.506	0.665	---
Sum of Factors	2.0	2.0	4.0	4.0	6.0

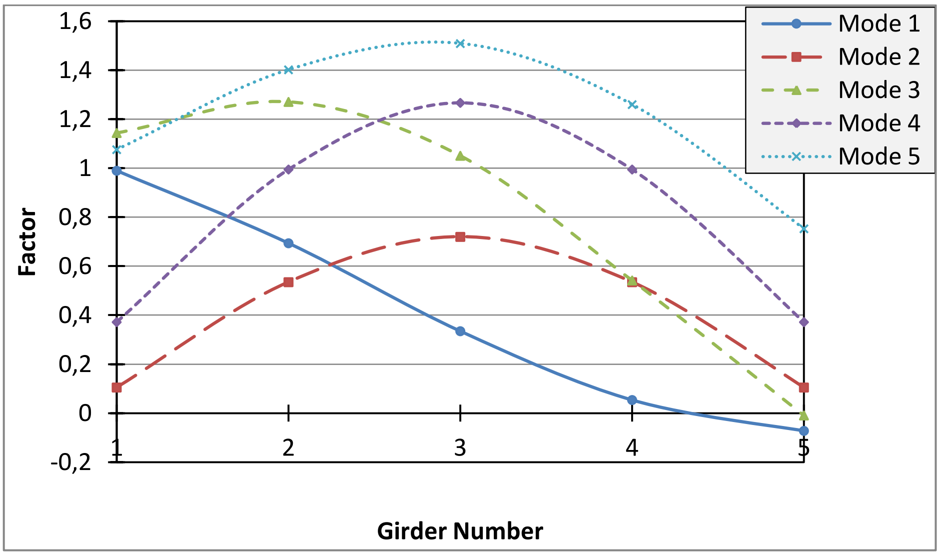

Figure 8. Variation of load distribution factors for different modes according to loading of 40-ton-truck.

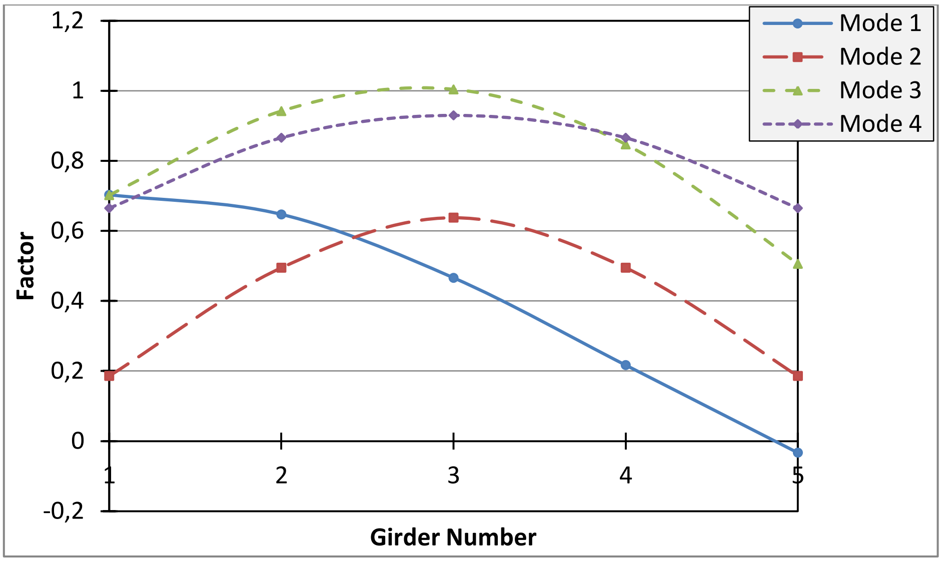

Figure 9. Variation of load distribution factors for different modes according to loading of 90-ton-truck.

For investigating the structural behavior against this unusual load (heavy truck), in the first, bridge is analyzed, and then results of moments and displacements in marked and arbitrary points (modes) are compared to normal loading of AASHTO [1]. Additionally, according to AASHTO conditions, maximum amounts of these parameters are determined for controlling the maximum power of section.

In this regard, design of bridge should be according to this unusual loading. Therefore, maximum capacity of flexural moment is determined.

5.1. Loading portion of the Internal Girder

Portion of the internal girder= $\frac{S}{1.68} = 1.49$

The maximum flexural moment for this two-simple-girder bridge under loading of 40-ton-truck is $\frac{289.2}{2} = 144.6\ \ ton.m$. So, loading portion of the internal girder is $1.49 \times 144.6 = 215.5\ \ ton.m$

Finally, according to effect of dead load from section of 4.1, the total moment for internal girder is $171.875 + 215.5 = 387.4\ \ ton.m$

5.2. Loading portion of the External Girder

Portion of the external girder= $\frac{S}{1.22+0.25S} = 1.356$

Live load= $1.356 \times 144.6 = 195.93\ \ ton.m$

Total moment= $171.875 + 195.93 = 367.81\ \ ton.m$

According to these maximum moments, the moment of internal girder is higher than external girder, therefore internal girder is considered.

$M_{Max} = M_{Internal\ Girder} = 387.4\ \ ton.m = 387.4 \times 10^5\ \ kg.cm\ ,\ I_{I.G.} = 4.146 \times 10^6\ \ cm^4$

$\left(\frac{MC}{I}\right)_{bottom} = \frac{387.4\times10^5\times120.7}{4.146\times10^6} = 1126.75\ \frac{kg}{cm^2}\ ,(\frac{MC}{I})_{top} = \frac{387.4\times10^5\times(150-120.7)}{4.146\times10^6} = 293.5\ \frac{kg}{cm^2}$

$(\frac{MC}{I})_{Max} = 1126.75\ \frac{kg}{cm^2}$

6. Displacements Results and Flexural Moment of Girders

In this section, the results of structural analysis under loading of 40 and 90-ton-truck for bridge in different modes are investigated, and also maximum amounts of displacement and flexural moment of girders are demonstrated in Table 3.

Table 3: Maximum amounts of displacement and flexural moment of girders

Truck	**Flexural moment (*ton.m*)**	**Displacement (*cm*)**
40 ton	150	0.98
90 ton	360	2.5

The tolerable moment from section of 5.1 is 215.5 *ton.m*, that it justifies amount of 150 *ton.m* from locating the 40-ton-truck. But, the amount of 360 *ton.m* from 90-ton-truck shows inappropriate in this design for loading. In this regard, girders should be strength against load of trucks. In order to strengthening of girders against unusual loading, two methods are considered: increasing the flexural stiffness of girders and increasing the torsional stiffness of girders.

7. Increase in Flexural Stiffness of Girders

AISC [4] allows 70 percent increase in surface of fin for reinforcing the girders. So, it proposes sheets with 20 *cm* width that shown in Fig. 10. According to this adjustment, the position of neutral axis and inertia moment is changed.

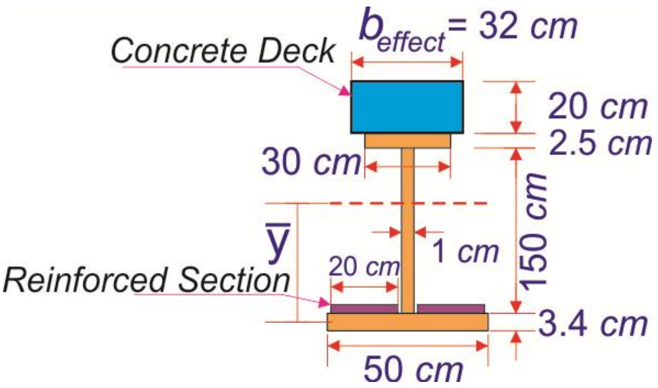

Figure 10. Section of strengthened girder.

$$\bar{y} = \frac{30 \times 2.5 \times 150 + 32 \times 20 \times 160 + 1 \times \frac{150^2}{2} + 2 \times 60 \times 3.2}{50 \times 3.4 + 30 \times 2.5 + 32 \times 20 + 150 \times 1 + 2 \times 60} = 108.57\ cm$$

$$I_G = 5.63 \times 10^6\ \ cm^4$$

7.1. Calculation of tolerable flexural moment for girder

According to the result of section of 5.2:

$$\left(\frac{MC}{I}\right) = \frac{M \times 120.7}{5.63 \times 10^6} = 1126.75\ \frac{kg}{cm^2}\ \Rightarrow\ M = 525.6 \times 10^5\ kg.cm = 525.6\ ton.m$$

$$525.6 = M_{D.L.} + M_{L.L.} = 171.875 + M_{L.L.}\ \Rightarrow\ M_{LL\,(allowable)} = 353.73\ ton.m$$

8. Increase in Torsional Stiffness of Girders

According to new researches by [5], by increase in torsional stiffness of girders, axis load distribution factors of truck is more balanced, therefore engineer will design the bridge for less load. So, it is necessary that consider a section with high torsional stiffness from first. But, in some specific bridges such as the bridge of this research that using this section was not considered, and also I-shape sections is used, the members should be reinforced against torsional forces. As a result, according to investigations by [6, 7], lateral bracing is considered. Fig. 11 illustrates reinforced section of bridge and specifications of it.

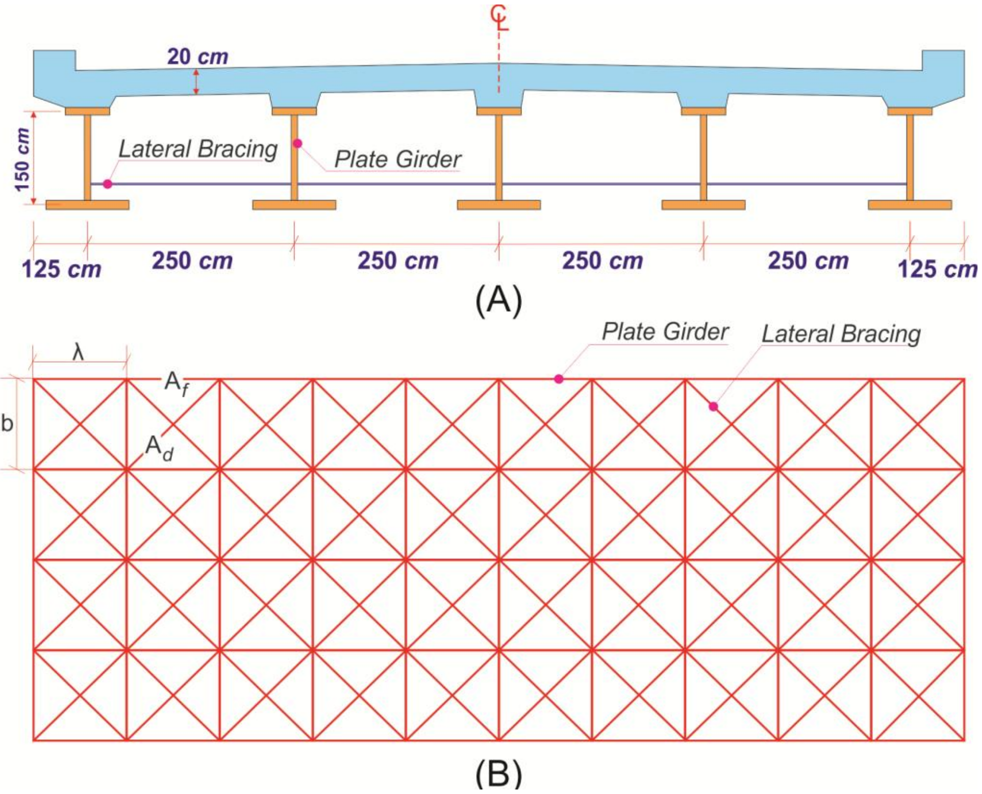

Figure 11. Increase in torsional stiffness of girders:

(A): Transvers section of bridge with horizontal bracing, (B): Vertical view of girders and bracings connection.

Fig. 12 shows specifications of stiffened quasi-box against torsional and flexural forces. So, equations and calculations of torsional stiffness according to this figure are as follows [6]:

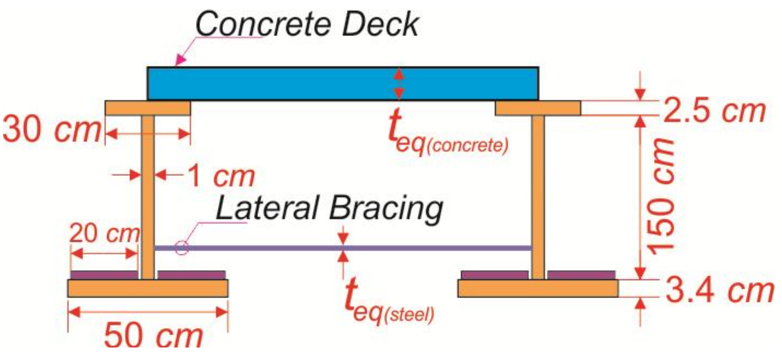

Figure 12. Illustration of stiffened quasi-box against torsional and flexural forces.

$A_f = 50 \times 3.4 \times 10^{-4} = 0.017\ m^2$

$t_{eq\ (concrete)} = \dfrac{20}{n} = \dfrac{20}{7.5} = 2.67\ cm\,, \qquad \lambda = 2.5\ m\,, 2b = 2.5\ m$

$d = \sqrt{\lambda^2 + (2b)^2} = 3.54\ m\,, \qquad E = 2.1 \times 10^6\,\dfrac{kg}{cm^2}\,,$

$G = 0.808 \times 10^6\,\dfrac{kg}{cm^2}$

Using $L\ 100 \times 100 \times 10$ for bracings: $A_d = 19.2\ cm^2$

$$t_{eq(steel)} = \frac{E}{G} \times \frac{2b\lambda}{\frac{d^3}{2A_d} + \frac{\lambda^3}{6A_f}} = \frac{2.1 \times 10^6}{0.808 \times 10^6} \times \frac{2.5 \times 2.5}{\frac{3.54^3}{2 \times 19.2 \times 10^{-4}} + \frac{2.5^3}{6 \times 0.017}} = 0.137\ cm$$

$$J = \frac{1}{3}\sum(bt^3 + \frac{4F^2}{\oint \frac{d_s}{t}}) = 2 \times 86195 \times 10^3 + \frac{4 \times (125 \times 250)^2}{\left[\frac{2 \times 125}{1} + \frac{250}{0.137} + \frac{250}{2.67}\right]} = 1.97 \times 10^6\ cm^4$$

F: Trapped surface between members of quasi-box-girder
According to the results of sections of 7 and 8:

$$I_1 = I_2 = I_3 = I_4 = I_5 = 5.63 \times 10^6\ cm^4, \qquad J_1 = J_2 = \frac{1.97 \times 10^6}{2} = 0.985 \times 10^6\ cm^4$$

$$J_3 = J_4 = J_5 = 1.92 \times 10^6\ cm^4$$

9. Investigation of Bridge Results for 90-ton-truck

The structure is analyzed for new features of this truck, and then load distribution factors between girders are calculated for 4 modes, that they are illustrated in Fig. 7. Table 4 gives load distribution factors of 90-ton-truck, and also variation of these factors for strengthening of structure are shown in Fig. 13. Therefore, maximum of flexural moment and displacement are demonstrated in Table 5.

Table 4: Load distribution factors of 90-ton-truck between girders

	Mode				
Girder Number	1	2	3	4	5
1	0.627	0.290	0.734	0.729	---
2	0.579	0.447	0.838	0.836	---
3	0.434	0.526	0.870	0.870	---
4	0.255	0.447	0.833	0.836	---
5	0.106	0.290	0.724	0.729	---
Sum of Factors	2.0	2.0	4.0	4.0	6.0

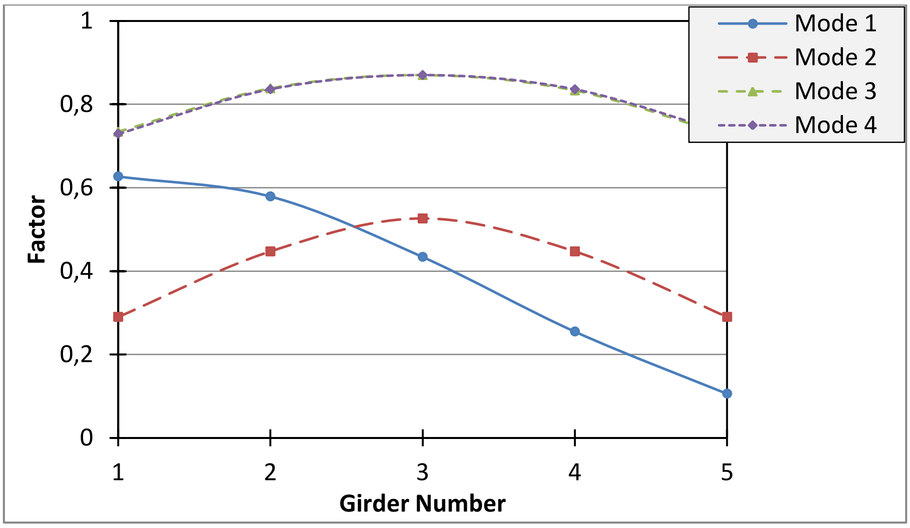

Figure 13. Load distribution factors for different modes of 90-ton-truck in strengthened bridge.

According to Table 4, maximum factor is 0.780, but Table 2 gives this maximum as 1.004. So, it shows decrease of 22.3 percent between two results.

Table 5: Maximum of flexural moment and displacement

Truck	**Loading System**	**Flexural moment (*ton.m*)**	**Displacement (*cm*)**
40 ton	*	150	0.98
90 ton	*	360	2.5
	**	320	1.6

* Coolie members of bridge without variation

** Coolie members of bridge against stiffened torsional and flexural forces

The maximum moment of flexural from loading of 90-ton-truck for stiffened girders is 320 *ton.m*, so this amount is lower than 360 *ton.m* for normal girders. Thus, it is suitable for allowable moment of girder in section of 7.1. Besides, decrease in maximum displacement of girder from 2.5 *cm* to 1.6 *cm* shows control of the capability of loading.

It goes without saying that, decrease in flexural moment of girders is due to increasing the torsional stiffness of girders and also decreasing load distribution factors of truck. Additionally, if girders do not stiffen against flexural moment, more reduction will happen. But, the bridge is strengthened due to controlling the displacement and inverse increase of the torsional and flexural stiffness of girders according to Table 5.

10. Conclusion and Results

In this research, the investigations show that torsional stiffness of longitudinal girders in steel slab-on-two-simple-girder bridges is very appropriate for balance in load distribution factors of truck between girders according to number and type of girders. As a matter of fact, increase in torsional stiffness according to relationship between flexural and torsional stiffness of girders with strip flexural stiffness of deck by orthotropic method is possible, and more increase in it, has neutral or negative effect on adjustment of load distribution factors in girders.

Additionally, increase in flexural stiffness of girders and significant role of it in load distribution can improve the torsional stiffness of girders in this theory.

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