WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.140661

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVIII ISSUE 2 2022

pp. 593 – 610

Research paper

Shear force distribution law of inclined webs box girder under live load

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Abstract: Inclined web box girders are widely used in urban areas because of their attractive appearance. However, there are few studies on the vehicle shear force distribution of this type of bridge. In this study, we established 62 three-dimensional finite element models in which the shear force of each web of the box girder can be extracted; furthermore, we investigated the shear force distribution law in webs of the box girder under live loads, including single-chamber and multichamber inclined web box girders. The main parameters studied include the number of vehicle lanes and chambers, slope of the inclined webs, and support conditions. The results reveal that an uneven distribution of web shear force exists in both the single-chamber box girder and multichamber girder under live loads, and the maximum value of the vehicle shear force distribution factor is greater than the average shear value shared by all webs. Therefore, the uneven distribution of shear force in the webs of the box girder cannot be ignored under eccentric vehicle loads. These values greatly exceed the safety factor of 1.15 that is used in conventional calculations.

Keywords: inclined web box girder, uneven distribution of web shear force, vehicle load, vehicle shear force distribution factor, shear force distribution

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1. Introduction

The interior of box girders is hollow; therefore, the girders are lightweight structures [1–5]. The box girder section is a closed thin-walled section; therefore, the box girder has greater torsional and flexural rigidity, and the top and bottom plates of the box girder have a large area to embed the rebar, which can effectively resist the flexural moment [6–9]. Therefore, box girders have superior mechanical properties and are widely used in bridge engineering [10–17].

The mechanical properties of box girders are complicated, which will have four deformation states: transverse bending, longitudinal bending, torsion and torsion deformation under eccentric load. Therefore, it is very necessary to study on the distribution law of box girder under loads. Xue et al. [18, 19] used the three-dimensional finite element method (FEM) to study the shear force distribution law in webs of box girders under dead loads. Based on the numerical analysis results, it is worth noting that the uneven distribution of shear forces in webs under live and dead loads cannot be ignored.

More research has been focused on the study of load distribution under live loads. A simplified method for calculating the distribution factor of a live load was proposed by Sharon et al. [20] and originated from Henry's method. Fanous et al. [21] proposed a simplified equation for calculating the live load distribution factors and considered factors including the span, spacing, and width of the girders. Based on classical slab theory, Devin et al. [22] proposed a load distribution characteristics method for beam-slab-type bridges. Bae and Olive [23] conducted a numerical analysis on 118 bridges under 16 overloaded vehicle conditions and proposed a modified load distribution factor equation. Deng et al. [24] investigated the impact of the wheel-line spacing of four-wheel dual-lane loads on the live-load distribution on slab-on-girder bridges and determined the load transfer function. Hazim et al. [25] conducted a study on the live load distribution coefficient of high-performance prestressed concrete beam bridges. The results showed that live-load distribution factors calculated based on the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) specifications (2017) [26] were significantly lower than the computed distribution factors based on measured girder strains owing to the live-loading test.

The live load distribution of box girder bridges is different from that of multislab bridges. Shin et al. [27] studied the live load distribution characteristics of box girder bridges and the applicable conditions of the AASHTO LRFD (1998) [28] specifications. Samaan et al. [29] used FEM to study the live load distribution factors of two-equal-span continuous curved box-girder bridges. Iman et al [30] studied the influence of torsional stiffness and live load position on the live load distribution factor of box girder bridges, Fatemi et al. [31] conducted a comprehensive numerical study on the load distribution mechanism of composite steel-concrete horizontally curved box girder bridges, and Choi et al. [32] conducted finite element analysis on 120 representative numerical model bridges and proposed a new set of equations to calculate the maximum stress, deflection, and flexural moment distribution factors for a two-span multicell box-girder bridge. Kong et al. [33] proposed a new empirical formula for the live load distribution factor of medium and small-span composite bridges with multiboxes.

Inclined web box girders have large cantilevers and an attractive appearance (Figure 1); therefore, they are very popular in urban areas. But there are few studies on the shear force distribution law of inclined web box girders under vehicle loads. In this paper, the shear force distribution law of an inclined web box girder under a live load is emphatically studied using three-dimensional FEM, in which the shear force of each web of the box girder can be extracted. The main research parameters studied include the number of vehicle lanes and chambers, slope of the inclined webs, and support conditions. Both single-chamber box girders and multichamber box girders are examined.

Fig. 1. Bridge with inclined webs box girder

2. Shear force distribution law of single-chamber inclined webs box girder

2.1. Model

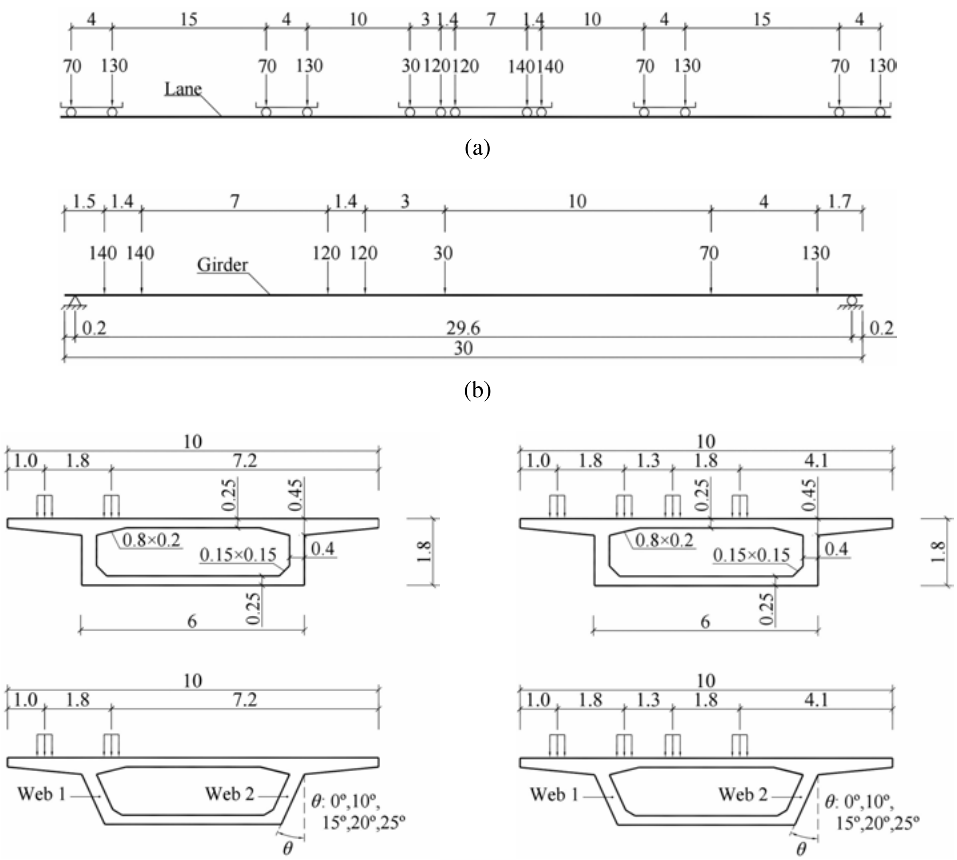
The internal force distribution of the single-chamber inclined web box girder is symmetrical under a dead load, but the shear force distribution is uneven under the asymmetrical arrangement of a live load.

The effective span of the simply supported box girder bridge is 29.60 m, and the height and width are 1.8 m and 10 m, respectively. The top and bottom plates have a thickness of 25 cm. Previous studies showed that the web thickness has an insignificant effect on the shear force distribution [18, 19]; therefore, this study considered a uniform web thickness of 40 cm.

The main research parameters of the shear force distribution law of a single-chamber inclined webs box girder under unbalanced vehicle loads include the following:

1. Slope of inclined web: The web rotates 0°, 10°, 15°, 20°, and 25° along the centre of the web (Figure 2c and 2d).
2. Support conditions: Two supports or three supports were set under the end diaphragm.
3. Number of vehicle lanes: Because the symmetrical arrangement of vehicles does not have an uneven distribution of shear forces in webs of a single-chamber inclined web box girder, only the case of an unbalanced vehicle load is studied, including one

unbalanced vehicle lane and two unbalanced vehicle lanes. The arrangements of one unbalanced vehicle lane and two unbalanced vehicle lanes are shown in Figure 2c and 2d. The vehicle load is QC-20 as specified by the Chinese code, which includes a heavy vehicle weighing 550 kN and an unlimited number of normal vehicles weighing 220 kN [34]. The vehicle load is expressed as a vehicle fleet (Figure 2a). To maximise the shear value of the shear extraction section, the arrangement of QC-20 in the direction of the longitudinal bridge is in accordance with Figure 2b.



(a) (b)

(c) One unbalanced vehicle lane (d) Two unbalanced vehicle lanes

Fig. 2. Web label and arrangement of unbalanced vehicle load (Unit: m, kN)

By combining the above influencing factors, 20 numerical models are obtained (Table 1). The naming rule for these models is S1(2)_L2(3)_Sp, where the number after ‘S’ represents the number of supports; the number after ‘L’ represents the lane number of live loads, and ‘Sp’ represents the slope of the side web. For example, S2_L1_25° indicates that the number model has two supports, one unbalanced vehicle lane, and an inclined web with a slope of 25°.

Table 1. Parameters of single-chamber box girder

Model label	Slope of web	Lane number	Support number	Description
S2_L1_S_p	0°, 10°, 15°, 20°, 25°	1	2	Girders with one lane and two supports
S2_L2_S_p		2	2	Girders with two lanes and two supports
S3_L1_S_p		1	3	Girders with one lane and three supports
S3_L2_S_p		2	3	Girders with two lanes and three supports

In this study, a three-dimensional finite element analysis model of a box girder is established by Midas/FEA, and the vehicle load QC-20 is conveniently applied on the deck (Figure 4a and 4b). According to the code [34] the most typical section for extracting shear is positioned at a distance of $3h/2$ (h is the height of the box girder) from the support (Figure 3).

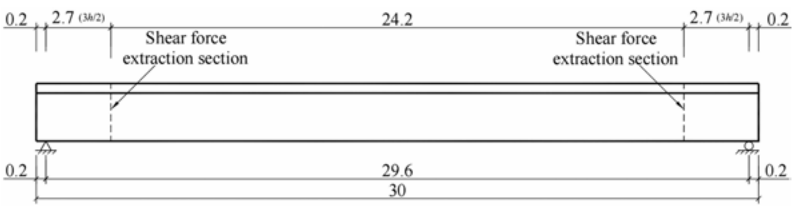
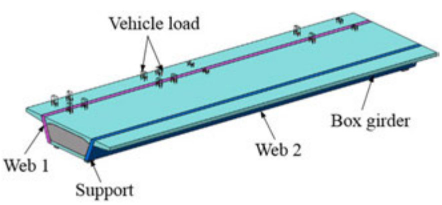
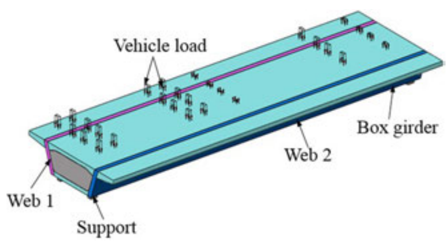


Fig. 3. Box girder shear extraction section (Unit: m)

The function of 'sum of the local internal forces' in Midas/FEA is used to extract the shear forces, which can extract the total internal force of a specific section and output all the internal force values in the form of text. The main internal forces of output include F_x (axial force in X direction), F_y (shear force in Y direction), F_z (shear force in Z direction), M_x (bending moment around X axis), M_y (bending moment around Y axis) and M_z (bending moment around Z axis) of the section. The specific shear extraction method can be found in a previous study [18, 19]. Three-dimensional finite element models of the single-chamber box girder are shown in Figure 4, with model S2L1_25° and model S2L2_25° as examples.



(a) Model S2L1_25°



(b) Model S2L2_25°

Fig. 4. Three-dimensional finite element model of single-chamber box girder

To characterise the uneven distribution of the web shear force, the vehicle shear force distribution factor η_v is defined as follows:

$$\eta_v = V_i / (V_a / N_w) \tag{2.1}$$

where: V_i – the shear force of each web; V_a – the shear force of the section, N_w – the number of box girder webs.

Significantly, shear force is shared by web, top and bottom plates under vehicle loads, and most of the shear force is shared by the web. In the formula (2.1), V_a is the shear force of the section, and V_i is the shear force of each web, so the value of $\sum \eta_{vi}$ should be slightly smaller than the value of N_w. In fact, the ratio of *the sum of vehicle shear force distribution factor of all webs* $\sum \eta_{vi}$ to *the number of webs* N_w is equal to the ratio of *the sum of the shear forces shared by each web* $\sum V_i$ to *the shear force of the section* V_a, that is $\sum \eta_{vi}/N_w = \sum V_i/V_a$.

2.2. Effect of slope of inclined web

Through internal force extraction, the shear force of the section ($3h/2$ from the support) is obtained and processed according to formula (2.1). Figure 5 shows the relationship between the vehicle shear force distribution factor η_v and the slope of the inclined web.

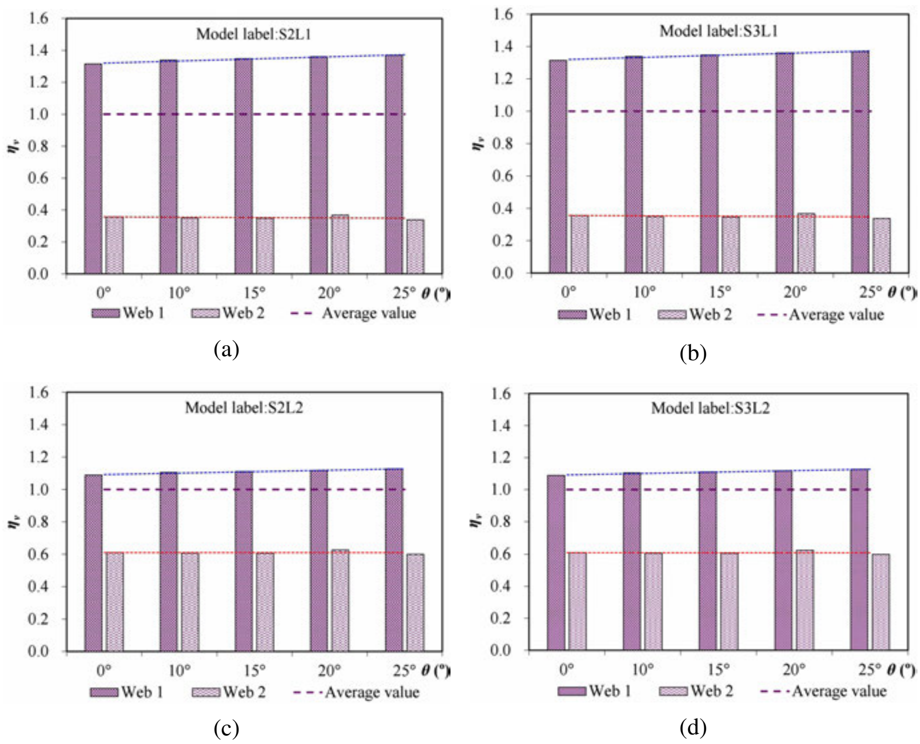


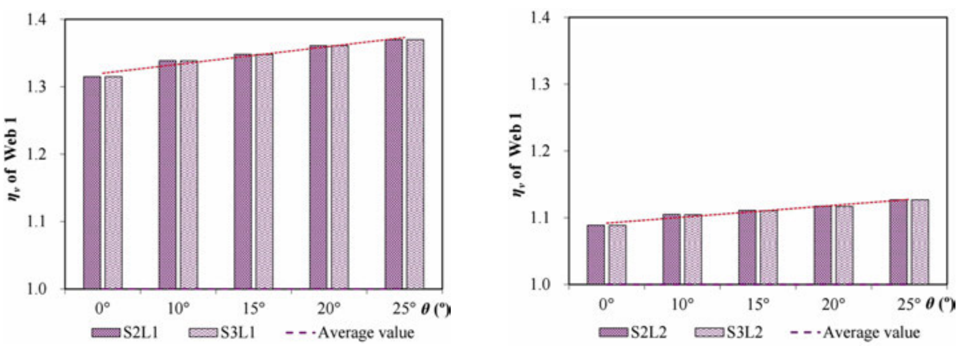
Fig. 5. Relationship between vehicle shear force distribution factor η_v and slope of inclined web

As shown in Figure 5, the vehicle shear force distribution factors of Web 1 on the side of the eccentric load of the four groups of models are all greater than 1.0, and the maximum value is 1.370, which is greater than the average shear value shared by all webs. Thus, the uneven distribution of shear force in the webs of the box girder cannot be ignored under unbalanced vehicle loads.

The trend lines show that the values of the vehicle shear force distribution factors of Web 1 increase with an increase in the inclination of the side webs, and vice versa for Web 2. However, the magnitude of the change in the values is small. Taking model S3L1 with the maximum change value as an example, the vehicle shear force distribution factor increases from 1.315 to 1.370, a difference of only 4.19%.

2.3. Effect of support condition

The following model groups are compared under two supports and three supports to reveal the influence of support conditions on the vehicle shear force distribution factor: (1) one unbalanced vehicle lane for model groups S2L1 and S3L1 and (2) two unbalanced vehicle lane for model groups S2L2 and S3L2. Figure 6 shows the vehicle shear force distribution factor of Web 1 under the condition of two supports and three supports.



(a) (b)

Fig. 6. Relationship between vehicle shear force distribution factor η_v and support conditions

The results reveal a slight influence of supports on the vehicle shear force distribution factor, regardless of using one or two unbalanced vehicle lanes, the is slight.

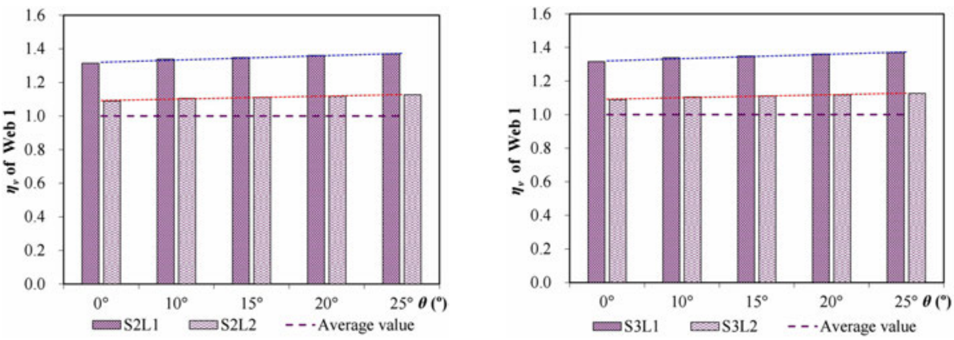
2.4. Effect of number of vehicle lanes

To study the effect of the number of vehicle lanes on the web shear force distribution, the analysis method of this study is as follows:

1. The shear force distribution factors of the model groups S2L1 and S2L2 are compared. Model groups S2L1 and S2L2 with the same support conditions (two supports) have one unbalanced vehicle lane and two unbalanced vehicle lanes, respectively.

2. Model groups S3L1 and S3L2 under the support conditions of the three supports are compared.

The number of vehicle lanes has a significant effect on the vehicle shear force distribution factor of the single-chamber box girder, as shown in Figure 7.



(a) (b)

Fig. 7. Relationship between vehicle shear force distribution factor η_v and vehicle lanes

The effect of the number of vehicle lanes is evident regardless of the number of unbalanced vehicle lanes. The effect of the uneven shear force distribution of an unbalanced vehicle lane is greater than that of two unbalanced vehicle lanes. For example, the vehicle shear force distribution factor of Web 1 of the S2L1 model group is 20.7%–21.80% greater than that of the S2L2 model group.

3. Shear force distribution law of multichamber inclined webs box girder

3.1. Model

The uneven distribution of web shear force exists in a multichamber inclined web box girder under a live load in an unbalanced vehicle load or balanced vehicle load. Preliminary research shows that the vehicle shear force distribution factor under a symmetrically arranged vehicle load does not exceed 1.15. Thus, the following introduces the situation of an unbalanced vehicle load.

In this study, the effect of the slope of inclined webs, support conditions, number of chambers, and lane arrangement on the shear force distribution law of box girder webs with multichamber inclined web box girders is considered:

1. Slope of inclined web: The web rotates 0°, 10°, 15°, 20°and 25°along the centre of the web.
2. Support conditions: Two supports or three supports were set under the end diaphragm.

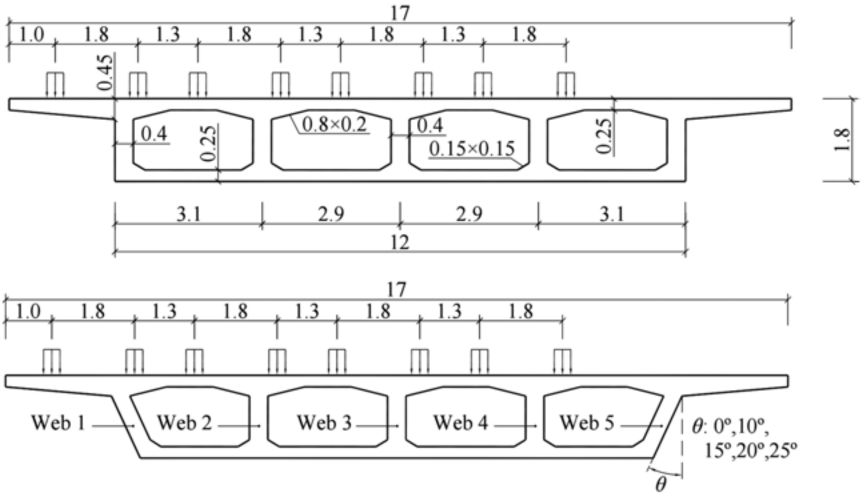


Fig. 8. Web label and arrangement of vehicle load (Unit: m)

3. Number of chambers: The number of chambers of the multichamber inclined webs box girder is 2, 3, and 4 (Figure 8).
4. The vehicle lane arrangement follows four unbalanced vehicle lanes. The longitudinal arrangement of the vehicle lane is shown in Figure 2b, and the transverse arrangement of the vehicle lane is shown in Figure 8. The shear force extraction section was at a distance of $3h/2$ away from the support (Figure 3).

Based on these influencing factors, 30 analysis models were obtained (Table 2).

Table 2. Parameters of multichamber inclined webs box girder

Model label	Slope of inclined web	Chamber number	Support number	Description
$C4\_S3\_S_p$	0°, 10°, 15°, 20°, 25°	4	3	Girders with four chambers, three supports, and four vehicle lanes
$C4\_S2\_S_p$		4	2	Girders with four chambers, two supports, and four vehicle lanes
$C3\_S3\_S_p$		3	3	Girders with three chambers, three supports, and four vehicle lanes
$C4\_S2\_S_p$		3	2	Girders with three chambers, two supports, and four vehicle lanes
$C2\_S3\_S_p$		2	3	Girders with two chambers, three supports, and four vehicle lanes
$C2\_S2\_S_p$		2	2	Girders with two chambers, two supports, and four vehicle lanes

The effective span, height, width, and thickness of the top and bottom plates of the research model of the simply supported multichamber box girder are 29.60 m, 1.8 m, 17 m, and 0.25 m, respectively. The web has a uniform thickness of 40 cm. The three-dimensional finite element model of the multichamber box girder takes the C4S2_25° model as an example, and the vehicle load is applied on the bridge deck, as shown in Figure 9.

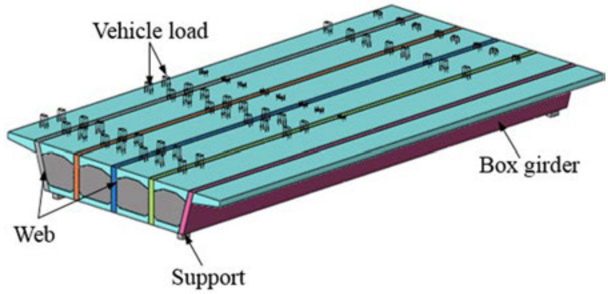


Fig. 9. Three-dimensional finite element model of multichamber box girder

3.2. Effect of slope of inclined web

Since the laws of the other model groups are similar, model group C4S2 is taken as an example to illustrate the effect of the slope of the inclined web on the distribution law of the web shear force. The relationship between the vehicle shear force distribution factor of Webs 1–5 of model group C4S2 and the slope of the inclined webs under four unbalanced vehicle lanes is shown in Figure 10.

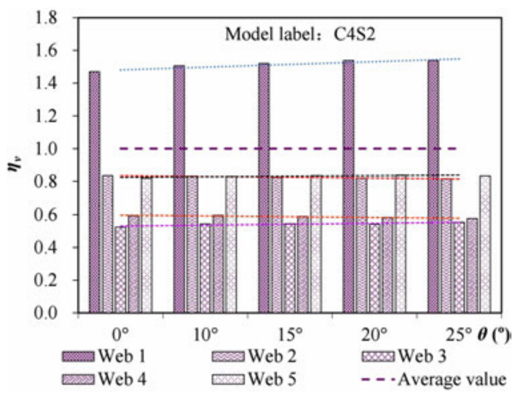


Fig. 10. Relationship between vehicle shear force distribution factor η_v and slope of inclined web of Model C4S2

All Web 1 values of all inclined box girders are greater than 1.0, and the maximum value is 1.538. These values greatly exceed the 1.15 safety factor used in conventional calculations. Therefore, full attention should be paid to the uneven distribution of the web under live loads in the design. The above research results show that the vehicle shear force distribution factors of Web 1 are greater than 1.0, which is unsafe. Consequently, in the following research, the focus is on the shear force distribution law of Web 1.

As can be seen from the trend line in Figure 10, with an increase in the slope of the inclined web, the vehicle shear force distribution factor of Web 1 increases. For example, when the slope of the inclined web of model group C4S2 changes from 0° to 25°, the vehicle shear force distribution factor of Web 1 increases only by 4.64%. This shows that the influence of the inclination angle is small.

3.3. Effect of support condition

The following model groups under two supports and three supports are analysed to reveal the influence of support conditions on the vehicle shear force distribution factor: (1) four-chamber model groups C4S3 and C4S2, (2) three-chamber model groups C3S3 and C3S2, and (3) two-chamber model groups C2S3 and C2S2.

According to Figure 11, increasing the number of supports for the multichamber box girder significantly alleviates the problem of an excessively large actual shear force distri-

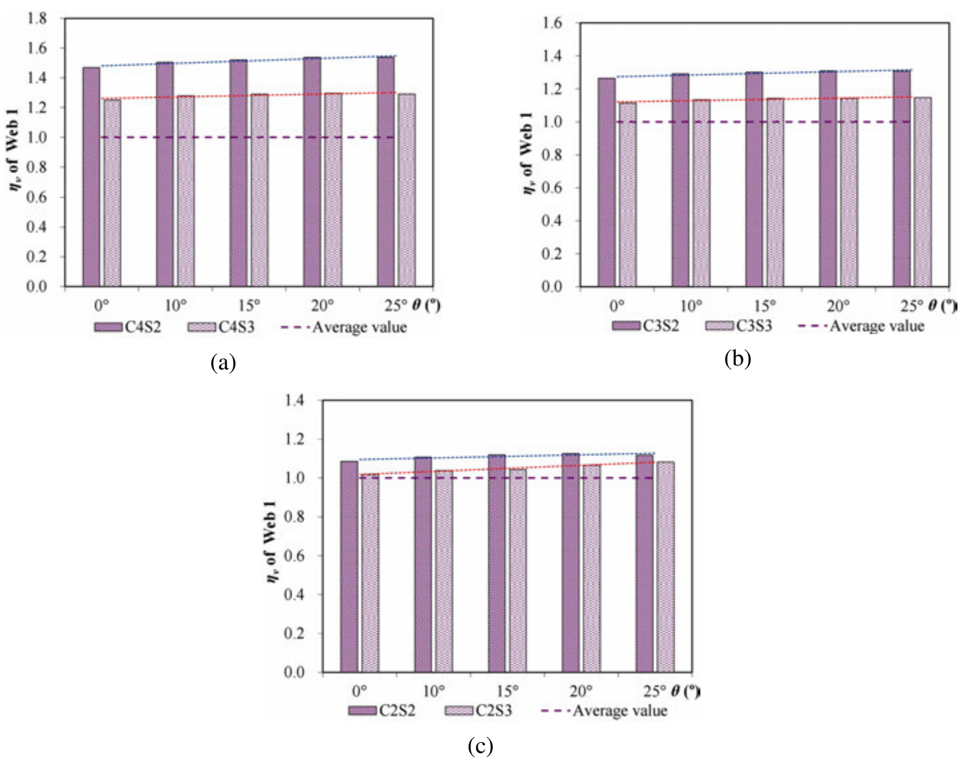


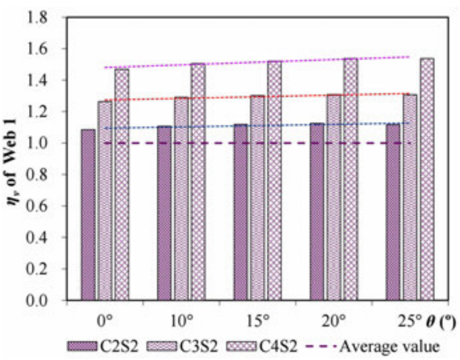
Fig. 11. Relationship between vehicle shear force distribution factor η_v and boundary conditions

bution on Web 1. With a decrease in the number of supports, the support reaction force acting on the multichamber box girder increases, which makes the shear force distributed by the web more uneven. For example, after model C4S3_25° (three supports) is changed to model C4S2_25° (two supports), the vehicle shear force distribution factor of Web 1 increases from 1.290 to 1.538, which increases by 19.22%.

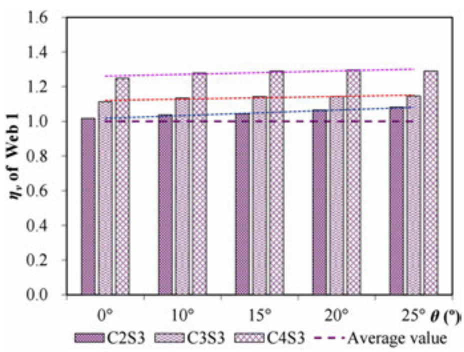
3.4. Effect of number of chambers

To study the effect of the number of chambers on the distribution law of the web shear force, the analysis method was as follows: model groups including C4S3, C3S3, and C2S3 with the same three supports were compared with those including C4S2, C3S2, and C2S2 with the same two supports.

As shown in Figure 12, regardless of number of supports, the vehicle shear force distribution factor of Web 1 increases with an increase in the number of chambers. For example, for S2_25° with two supports and a slope of the inclined web at 25°, the vehicle shear force distribution factor of Web 1 changed from 1.117 to 1.538, which increased by 37.69% when the number of chambers increased from two to four, indicating that the number of chambers has a greater effect on the shear distribution law of the box girder web than the number of supports.



(a)



(b)

Fig. 12. Relationship between vehicle shear force distribution factor η_v and number of chambers

4. Shear force distribution law in longitudinal bridge under live load

The shear force distribution law in longitudinal bridges under live loads is an important research topic. Models S2L1_25° and C4S2_25° were used to study the shear force distribution law of the single-chamber box girder and multichamber box girder, respectively.

In the longitudinal bridge, 14 shear extraction sections were selected to extract the shear force (Figure 13).

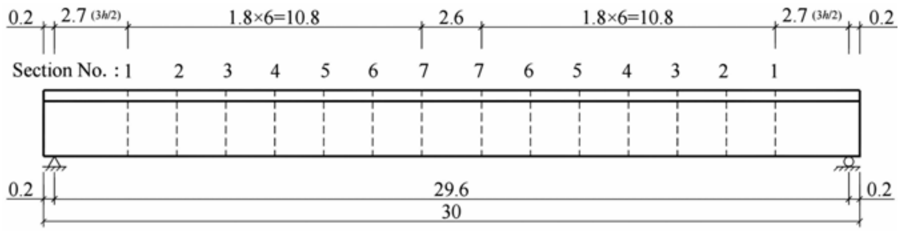
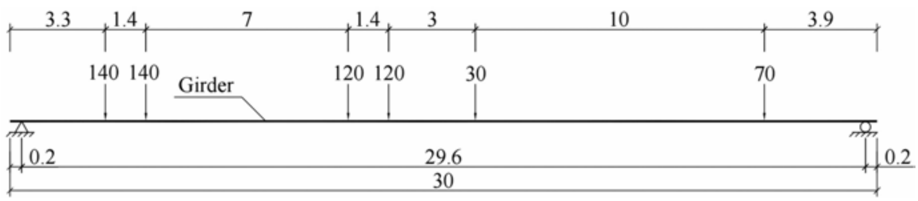
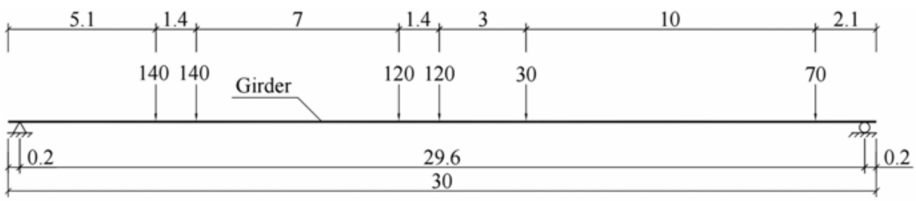


Fig. 13. Box girder longitudinal shear extraction section (Unit: m)

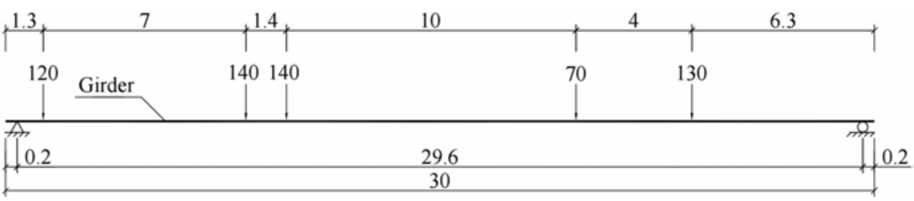
The study found that when the shear force of a certain section is the largest under a certain vehicle arrangement, the corresponding vehicle shear force distribution factor is also the largest. The most unfavourable arrangement of vehicle loads corresponding to Sections 2–7 is shown in Figure 14.



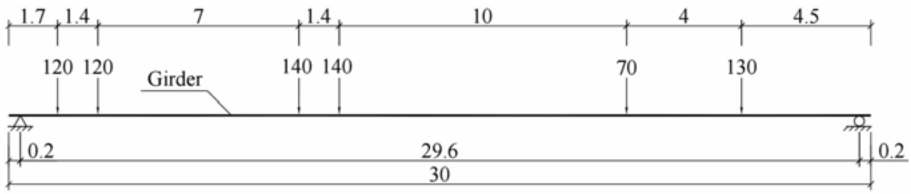
(a) Vehicle load arrangement of section 2



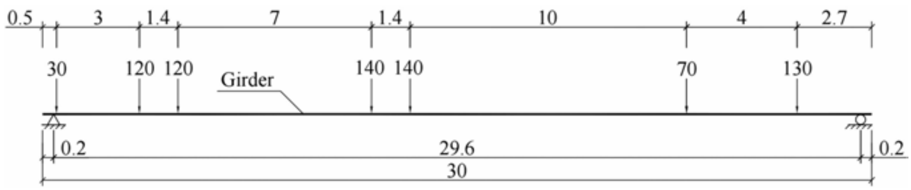
(b) Vehicle load arrangement of section 3



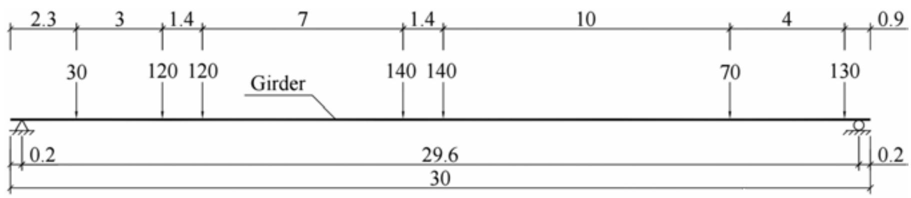
(c) Vehicle load arrangement of section 4



(a) Vehicle load arrangement of section 5



(b) Vehicle load arrangement of section 6



(c) Vehicle load arrangement of section 7

Fig. 14. Vehicle load arrangement in longitudinal bridge (Unit: m, kN)

Figure 15 shows the relationship between the vehicle shear force distribution factor of Webs 1 and 2 of the S2L1_25° and C4S2_25° models and the longitudinal position of the box girder.

In Figure 15, F represents the shear force of box girder web and L represents the longitudinal coordinates of box girder.

Figure 15a shows that as the shear extraction section approaches the midspan of the box girder, the vehicle shear force distribution factor of Web 1 shows a general increasing trend. However, the shear force value of Web 1 at the section 7 is significantly lower than that at section 1, as shown in Figure 15b.

From Figure 15c and 15d, it can be seen that as the shear force extraction section continues to approach the midspan of the box girder, the vehicle shear force distribution factor of Web 1 generally shows a decreasing trend overall, and the value of the shear force on Web 1 also decreases.

In general, special attention should be paid to position $3h/2$ away from the support of Web 1, where the shear value is the maximum and is the control section of the shear design.

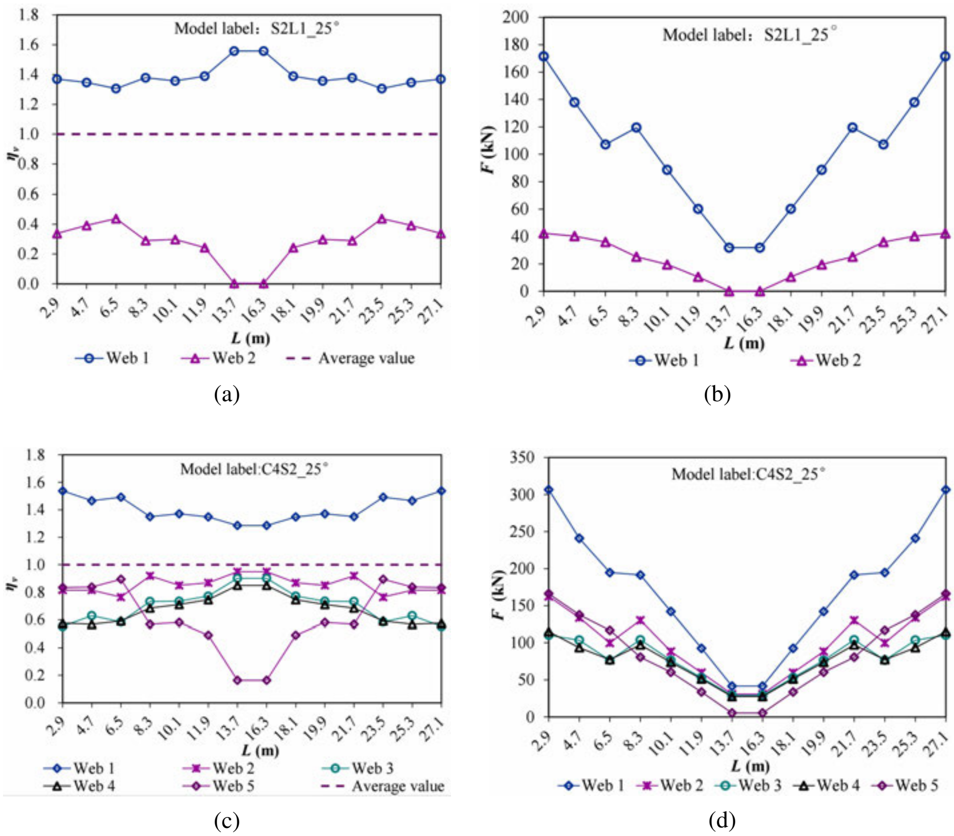


Fig. 15. Distribution law of web shear force in longitudinal bridge

5. Conclusion

In this study, the shear force distribution law of a box girder under a live load is studied. The main conclusions are as follows:

1. An uneven distribution of web shear force exists in both single-chamber box girders and multichamber girders under live loads. The maximum value of the vehicle shear force distribution factor η_v is 1.538, which is greater than the average shear value shared by all webs; therefore, the uneven distribution of shear force in the webs of the box girder cannot be ignored under eccentric vehicle loads. These values greatly exceed the 1.15 safety factor used in conventional calculations. Therefore, full attention should be paid to the uneven distribution of the web under live loads in the design.
2. For single-chamber box girders, the slope of the inclined web and the number of supports have little influence on the shear force distribution in webs, but the number of vehicle lanes has a great influence. Compared with the S2L2 model group, the

vehicle shear force distribution factor of Web 1 of the S2L1 model group increased by 20.5–21.80%.

3. The supports and chambers have a significant impact on the shear force distribution in the webs of the multichamber box girder. As the number of supports decreases and the number of chambers increases, the value of the vehicle shear force distribution factor η_v increases significantly. However, the effect of the slope of the inclined web is small.
4. The uneven distribution of shear force in the webs of the box girder cannot be ignored under eccentric vehicle loads. Moreover, these values were turned out to be larger than the existing values used in the conventional calculations. The maximum value of the vehicle shear force distribution factor and shear force is at a position $3h/2$ away from the support. In other words, this position should be used as the control section of the shear design of the box-girder bridge. Therefore, it is necessary to pay attention to the uneven distribution of the web shear force of the box girder in the bridge engineering.

Under vehicle loads, the uneven distribution of shear force in the webs of the box girder should be paid enough attention. In the future, it is suggested to carry out further research from two aspects of curved box girder bridge and steel box girder bridge.

Acknowledgements

This research was funded by the Scientific Research Project of the Educational Department of Liaoning Province (LNZD 202005) and the financial support from the Project of the MOE Key Lab of Disaster Forecast and Control in Engineering of Jinan University (20200904005). The authors would like to thank Editage (http:/www.editage.cn) for English language editing.

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Received: 25.11.2021, Revised: 08.02.2022