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SIMPLIFIED LOAD DISTRIBUTION FACTORS FOR FIBER REINFORCED POLYMER COMPOSITE BRIDGE DECKS

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Abstract. In recent years, researchers have investigated the load distribution factors due to vehicle wheel loads. Several load distribution factors for fiber reinforced polymer deck-steel stringer bridge systems have been proposed. Unfortunately, these load distribution factors are only used for each particular fiber reinforced polymer bridge deck system. Therefore, the objective of the research effort is to present the load distribution results of a parametric study using finite element analysis. The simplified load distribution factors were developed herein. The bridge parameters for this study were stringer spacing, bridge span, width of bridge models, types of fiber reinforced polymer bridge decks and numbers of traffic lanes. The bridge responses under various wheel loading conditions were investigated. The simplified distribution factors based on "*S*-over-factor" formula were proposed and compared with the load distribution factors obtained from specifications, analytical and field data. The load distribution results for this present study were correlated to the previous research data. The upper and lower bound limit of the load distribution factors were presented to purpose of preliminary guidelines.

Keywords: fiber reinforced polymer (FRP), composites, bridge, deck, finite element, load distribution.

1. Introduction

Currently, fiber reinforced polymer (FRP) composite materials are gaining greater acceptance as the materials of choices for highway bridge decks. Compared to conventional concrete decks, FRP bridge decks have high specific stiffness and strength ratios, excellent corrosion resistance leading to longer service life. Due to weight reduction and modular concepts in FRP bridge deck members, transportation and installation are rapidly done with lower need for heavy erection equipments.

Over the last two decades, many FRP bridge deck systems have been successively constructed. To understand the structural performance and behaviour of FRP bridge deck systems, a large number of research works on FRP bridge deck modules and systems were comprehensively studied. The FRP bridge deck systems were structurally evaluated through laboratory experiments and field studies (Deepthi 2005; Hayes *et al.* 2000; Howard, GangaRao 2009; Kumar *et al.* 2003; Nagaraj, GangaRao 1997; Sennah, Kennedy 1998; Sotiropoulus *et al.* 1995; Zureick *et al.* 1994). The FRP bridge deck responses using finite element method compared with experimental data were done by numerous researches (Alagusundaramoorthy, Reddy 2008; Kim *et al.* 2005; Lee *et al.* 2007; Prachasaree *et al.* 2006, 2009).

One of important issues concerning the design of FRP bridge deck systems has been focused on the development of load distribution factors. In recent years, several researchers have extensively investigated the load distribution among girders due to vehicle loads experimentally and analytically (Liu *et al.* 2008; Moses *et al.* 2006; Tarhini, Frederick 1992; Turner *et al.* 2004; Zhang, Cai 2007; Zokaie *et al.* 1992). However, there is a little progress in the wheel load distribution on FRP deck-stringer bridge systems. Several proposed load distribution factor equations are quite specific for specific FRP bridge deck system, with no generic load distribution factors published in literature so far.

The present study aims to fill this need for design and analysis of FRP bridge deck systems, conducting parametric study of FRP bridge deck behaviour under vehicular loads. The parametric study through finite element

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simulation, including influence of various bridge deck parameters on transverse load distribution have been carried out. The three dimensional models of FRP bridge deck systems are validated by comparing the data with the experimental results from laboratory and field tests (Howard, GangaRao 2009; Liu *et al.* 2008; Moses *et al.* 2006; Turner *et al.* 2004; Zhang, Cai 2007).

In this study, simplified load distribution factors based on single parameter "*S*-over-factor" are proposed due to ease and simplicity in applying these semi-empirical equations by practicing engineers according to the National Cooperative Highway Research Program (NCHRP), 12–26 formula (Zokaie *et al.* 1992). Generally, design community prefers and seeks to simpler and less complex wheel load distribution equations.

2. Multi-cellular FRP bridge deck

Two FRP bridge deck types, ProDeck 8 (high profile) and ProDeck 4 (low profile), were modelled in this parametric study. Both FRP bridge decks are produced by pultrusion process. The high-profile rectangular deck module with a diagonal stiffener known as ProDeck 8 was developed with fiber volume fraction of ~54%. The following three different laminates of ProDeck 8 are: 1) CDBM 3415 (multi-directional fabric laminate with orientation and stacking sequence [0°/45°/–45°/CSM]) 2) CDB400 (bi-directional fabric laminate of [45°/–45°]) and 3) continuous strand roving.

For ProDeck 4, the low profile rectangular deck module was also designed with fiber volume fraction (~50%) and three different laminates: 1) CDBM 3415 [0°/45°/–45°/CSM]; 2) DDBM 4015 (multi-directional fabric laminate [45°/90°/–45°/CSM]); 3) continuous strand roving. Moreover, the high elongation polymer resin used for ProDeck 4 and ProDeck 8 was vinyl ester resin. Unlike conventional engineering materials such as steel and concrete, the FRP composite materials exhibit thermo-mechanical properties of varying magnitudes in different directions.

To determine FRP deck stiffness, the stiffness of each laminate must be evaluated through material properties. Laminate properties defined as the interaction properties between the fiber and matrix of the composite are simply calculated using micro-mechanics based on the rule-of-mixture. In general, fiber and matrix properties are obtained from the manufacturer. The properties of all laminates used to model ProDeck 4 and ProDeck 8 deck systems are summarized in the Table 1. Additionally, layer construction and laminate stacking sequence of both FRP deck modules are presented in Fig. 1.

Table 1. Mechanical properties of laminates used for ProDeck 4 and ProDeck 8

FRP Deck	Laminate	E_{11}, 10^4 MPa	E_{22}, 10^4 MPa	G_{12}, 10^4 MPa	ν_{12}
ProDec 4	CDBM3415	3.84	0.94	0.47	0.27
	DDBM4015	3.88	0.95	0.46	0.28
	Roving	4.24	1.04	0.25	0.28
ProDeck 8	CDBM	3.38	0.58	0.24	0.26
	CDB 400	3.59	0.61	0.29	0.26
	Roving	3.45	0.59	0.24	0.26

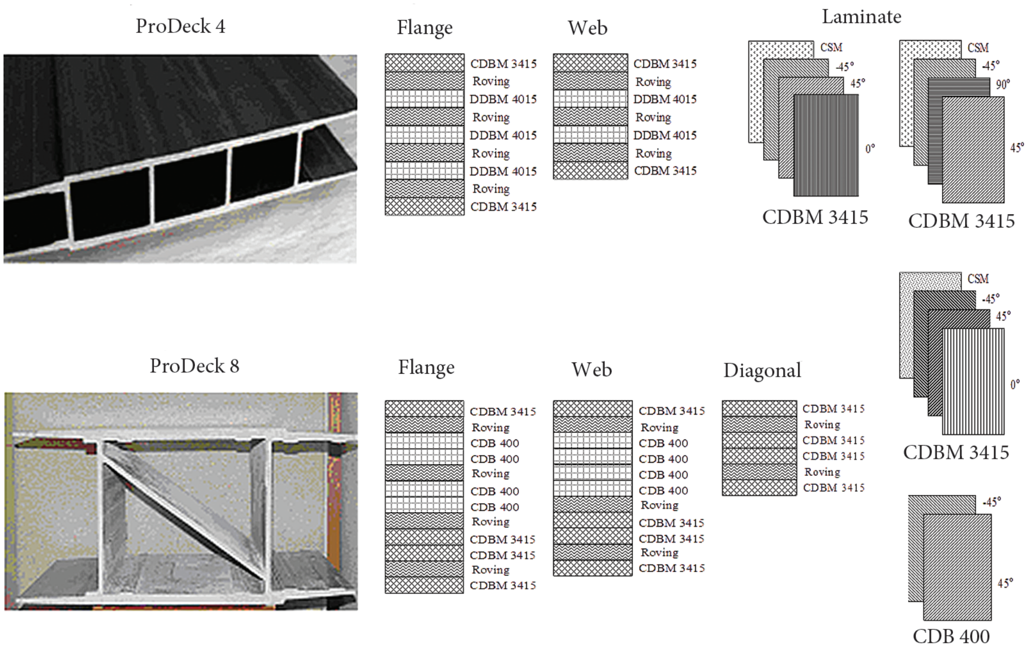


Fig. 1. Layer construction and laminate stacking sequence

Table 2. Bridge model parameters

Bridge model	Parameters							
	Deck type	Bridge length, m	Traffic lane	No. of stringer	W_{total}, m	$W_{traffic}$, m	*S*, m	*D*, m
M 2L7S				7 (W24×110)			1.20	1.05
M 2L5S	ProDeck 4	12	2 lanes	5 (W24×110)	9.50	8.53	1.83	0.99
M 2L4S	ProDeck 8	18		4 (W24×110)			2.29	1.20
M 3L10S				10 (W36×150)			1.20	1.10
M 3L7S	ProDeck4	12	3 lanes	7 (W36×150)	13.50	12.20	1.83	1.01
M 3L6S	ProDeck8	18		6 (W36×150)			2.29	0.77

3. FRP bridge geometry

A non skew single span, two and three lane, steel stringers stiffened with FRP decks were selected to perform the structural responses in the present study. All bridge superstructure models were assembled using (*H*-beam) straight steel stringers and multicellular FRP bridge decks. Typical bridge models were presented in Fig. 2. The width of bridge models was chosen to be a constant 9.50 m and 13.50 m for two and three traffic lanes, respectively. Two different span lengths of single span bridges were selected to be 12 m and 18 m. The FRP bridge decks, ProDeck 4 and ProDeck 8, rested on straight steel stringers (W24×110) and (W36×150) for bridge models with 12 m and 18 m span length, respectively.

The various steel stringer spacing for two and three traffic lane bridge models were considered to be 1.20 m, 1.83 m and 2.29 m. To determine wheel load distribution factor, the design trucks were located at a location on FRP bridge deck modules to produce the maximum stringer responses. The design trucks were placed side by side on the top surface of FRP bridge deck models. The separation distance between any two adjacent design truck loads was about 1.22 m (wheel to wheel). Thus, the number of the design trucks on FRP bridge models was dependent upon the width of traffic lanes (3.65 m). Bridge model parameters of ProDeck 4 and ProDeck 8 are summarized in Table 2.

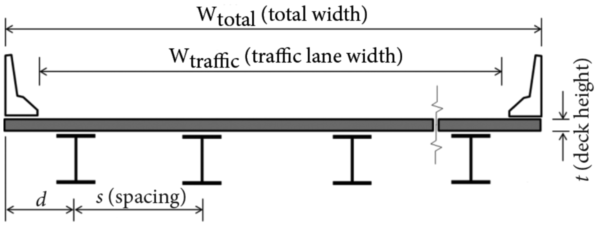


Fig. 2. Bridge geometry

4. Bridge loading

The AASHTO (American Association of State Highway and Transportation Officials) HS25 trucks were selected to simulate the design truck loading conditions. There are six different bridge models with various truck loading conditions. Totally, 9 cases of truck loading conditions were

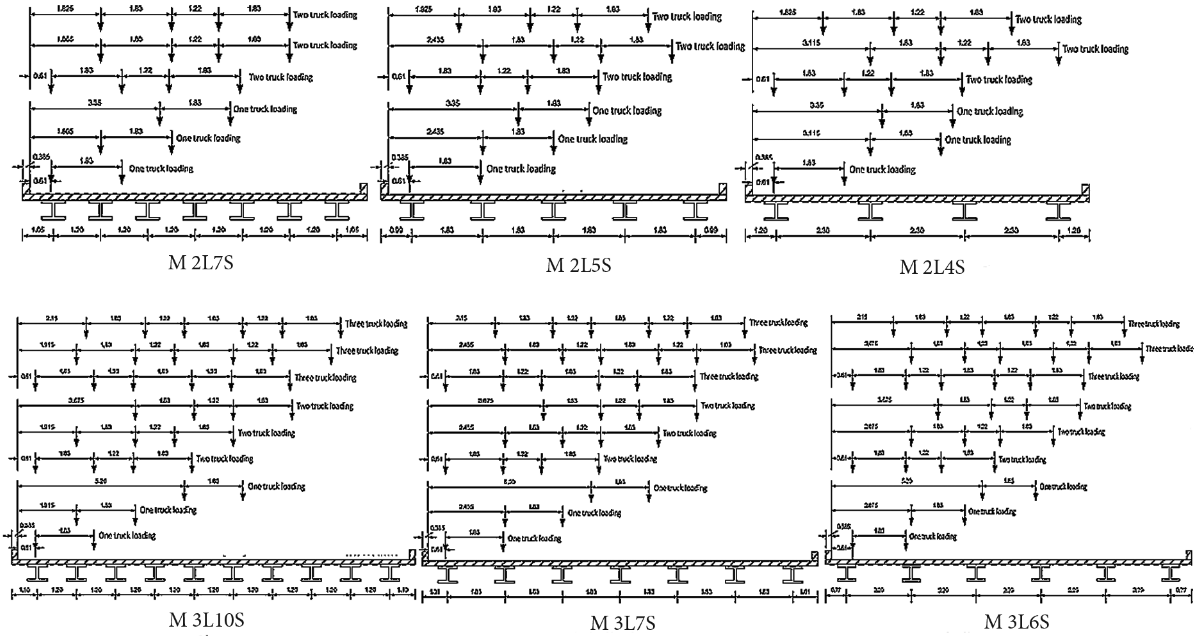


Fig. 3. Bridge models and loadings

investigated in this study. For one truck loading conditions, there are 3 different conditions as follows: 1.1) positioned on the side of the traffic surface; 1.2) the left tire directly over the centreline of the first interior stringer; 1.3) the middle of the traffic width. The remaining two truck loading conditions also consisted of three load cases: 2.1) the left tire of the left truck located on the side of the traffic surface, 2.2) the left tire of the left truck directly over the centreline of the first interior stringer and 2.3) the centre line between both trucks corresponding to the centre line of the traffic width. For three truck loading conditions, all three load cases were set-up to match with the two trucking loading conditions. A summary of the bridge models and design truck loading conditions is shown in Fig. 3.

5. Load distribution factor

Load distribution factor (LDF) is defined as a load fraction resisted by a supporting stringer under the bridge deck. It is important that the load distribution factors for FRP deck bridges must be evaluated in a way that the supporting steel stringers are appropriately designed. In practical design, the wheel load distribution factors are used to estimate the live load on each supporting stringer. To evaluate wheel live load transmitted to each steel stringer, the wheel load distribution factor was determined using Eq (1) developed by (Sotiropoulos *et al.* 1995)

$$LDF_k = \frac{\varepsilon_k}{\sum_{i=1}^{n} \varepsilon_i}, \tag{1}$$

where ε_k – strain of stringer (k); ε_i – strain of any stringer (i).

6. Finite element modelling

In this study, three dimensional bridge models were generated by using the commercial finite element program. MSC Patran was used as a pre- and post-processor with MSC Nastran as a solver. The finite element models based on linear elastic analysis are adopted in this parametric study. In general, the design load conditions are well below the critical stress leading to nonlinear geometry and material behaviour of bridge system models (Wan *et al.* 2005). All element responses were assumed to be linearly elastic and small deformations. Bridge geometry, nodes, elements and element meshes were automatically generated by MSC Patran.

The FRP bridge decks were modelled using orthotropic laminated shell elements. The element had 6 degrees at each node (translations in the nodal x, y, and z directions and rotations about the nodal x, y and z axes). All parts of the finite element FRP deck models were considered to be perfectly bonded together. The material properties of FRP deck models were taken from Table 1. The fiber orientation in each layer of all laminates was followed by the fiber architecture as shown in Fig. 2. For steel stringers, the quadrilateral isotropic shell elements were used to model flange and web steel stringers. The parametric study by (Tarhini, Frederick 1992) showed that the effect of cross bracing could be negligible on the load distribution factors. Therefore, cross bracings were not considered in this study. For support conditions, the roller (constrained in bridge x and z direction) and pined (constrained in bridge x, y and z direction) supports were assigned at the end of steel stringers.

In addition, the FRP decks and steel stringers were completely connected, thus the composite action at the FRP deck and stringer interfaces to be 100% for all finite element bridge models. To simulate the truck wheel loading on the FRP decks, patch load over an area of 25.4×50.8 cm was concentrically applied to the top surface of FRP decks.

7. Verification of finite element bridge models

The finite element bridge models were validated and calibrated through the experimental data. The deflection and load distribution factors obtained from laboratory experiments were compared with the analytical results of finite element bridge models. The finite element bridge model based data were compared with the laboratory testing (Howard, GangaRao 2009). Details of the laboratory experiments are given as follows: two different FRP bridge deck systems were conducted under static wheel loadings. The FRP bridge deck system was fabricated by joining five FRP deck modules with Ashland's polyurethane resin (pliogrip).

The first system was simply supported on two steel stringers with 345 cm spacing. For the second system, FRP bridge deck was positioned on three steel stringers with 173 cm spacing. Three different static loading conditions were performed to evaluate structural responses. The FRP deck systems and loading conditions are summarized in Fig. 4.

It was found that the finite element results agreed well with the experimental results. The relative deflection of FRP deck systems was in agreement with the finite element results as shown in Table 3. The steel stringer and deck deflections tend to reduce as support spacing and number of stringers decreased. The global structural stiffness of FRP bridge deck system decreases with increasing of stringer spacing and fewer stringers. The deflection responses of FRP deck-stringer systems satisfied the maximum allowable global deflection of stringer (clear span/800). For relative deflections, the max percent differences (between experimental and finite element results) were found to be 7.5%. The relative deflection limit state was proposed to be 0.2% of spacing (centre to centre) of stringers (GangaRao, Shekar 2002). The relative deflection limit was violated by FRP bridge deck systems only for load Case 1. The high stresses and strains in the FRP deck flange induced by stringer warping and lateral torsional effects may lead to the stiffness reduction of the FRP deck system. The magnitude of the stringer warping was severe due to excessive spacing that causes the FRP bridge deck systems to beyond the relative deflection limit. The resulting load distribution factors for the steel stringers were also reported in Table 3. The load distribution factor obtained from the finite element results varies between 0.23 and 0.80. The max load distribution factor occurred at the mid supporting stringer

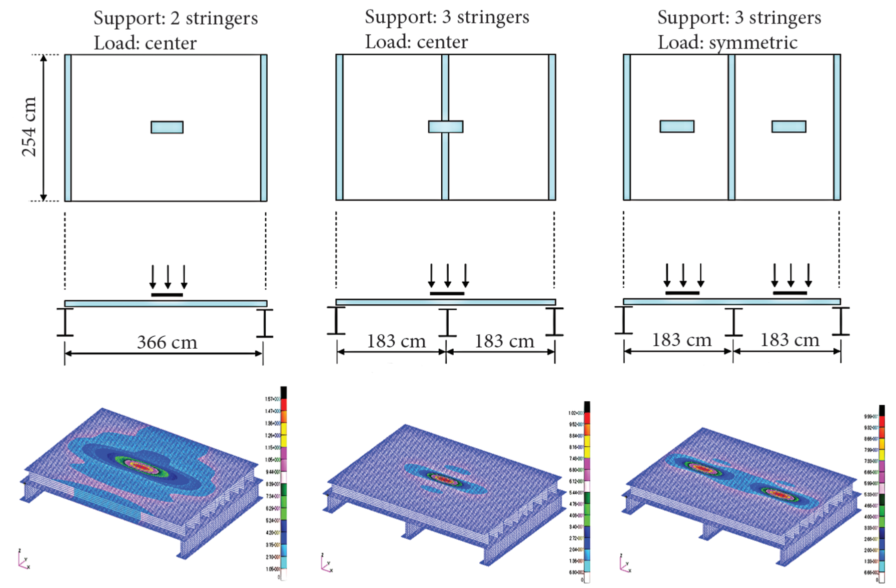


Fig. 4. Finite element models simulated by laboratory experiments

Table 3. Comparison between finite element and experimental results for FRP deck systems

Method	Load case	Applied load, kN	Average max deflection, cm		Relative deflection, cm	Load distribution based on strain, %		
			Stringer	FRP deck		Stringer Right	Stringer Mid	Stringer Left
Experiment	Case 1	89.0	0.170	1.199	1.029	60	–	40
Finite element			0.068	1.079	1.011	50	–	50
Experiment	Case 2	89.0	0.106	0.146	0.040	8	84	8
Finite element			0.082	0.119	0.037	10	80	10
Experiment	Case 3	177.9	0.170	0.516	0.346	23	50	27
Finite element			0.112	0.435	0.323	23	54	23

under load Case 2. The percent difference of the max load distribution factors between the finite element and experimental results was approx 5%.

8. Parametric study

A total of 180 FRP deck stringer bridge models were investigated through finite element simulation (Fig. 5). The load distribution factors in the present study were compared with the previous research data obtained from fields, laboratory experiments, and analytical methods. Four parameters: 1) stringer spacing; 2) bridge span; 3) width of bridge models; 4) types of bridge cross section were mainly considered under 9 cases of truck loading conditions as mentioned above. In terms of influence of bridge span and width, the average percent differences of the load distribution factors was found to be: 1) 3.1% – for the bridge models (having the same stringer spacing and width of bridge models); 2) 2.4% – for the bridge models (having the same stringer spacing and span length), respectively. It was also observed that the percent difference of the load distribution factor tended to decrease as the span length and width of the bridge models increased. The difference in the load distribution factors of the bridge models with different FRP deck cross sections (ProDeck 4 and ProDeck 8) was less than 4.7 %. From analytical results of this parametric study, it was seen that the load distribution factors were less significantly affected by variations in span length, bridge width and cross sectional types. ProDeck 4 and ProDesk 8 were produced by the same manufacturer. The fiber architecture and material properties of both ProDeck 4 and ProDeck 8 were quite similar. The experimental evaluations in the structural responses at the member level provide about 10% difference between both FRP decks (Deepthi 2005; Howard, GangaRao 2009; Prachasaree *et al.* 2006, 2009). Thus, the effect of FRP deck materials was not considered in this parametric study. However, it was observed that the load distribution factors increased with an increase in stringer spacing. The average percent difference in the load distribution factors was about 21% for the bridge models with various stringer spacing. Thus, the largest contribution to the load distribution factor of FRP deck – stringer bridges is stringer spacing (S) while other parameters have a less significant influence on the load distribution factors.

The corresponding plots of the load distribution factors in terms of spacing are presented in Fig. 6. To provide

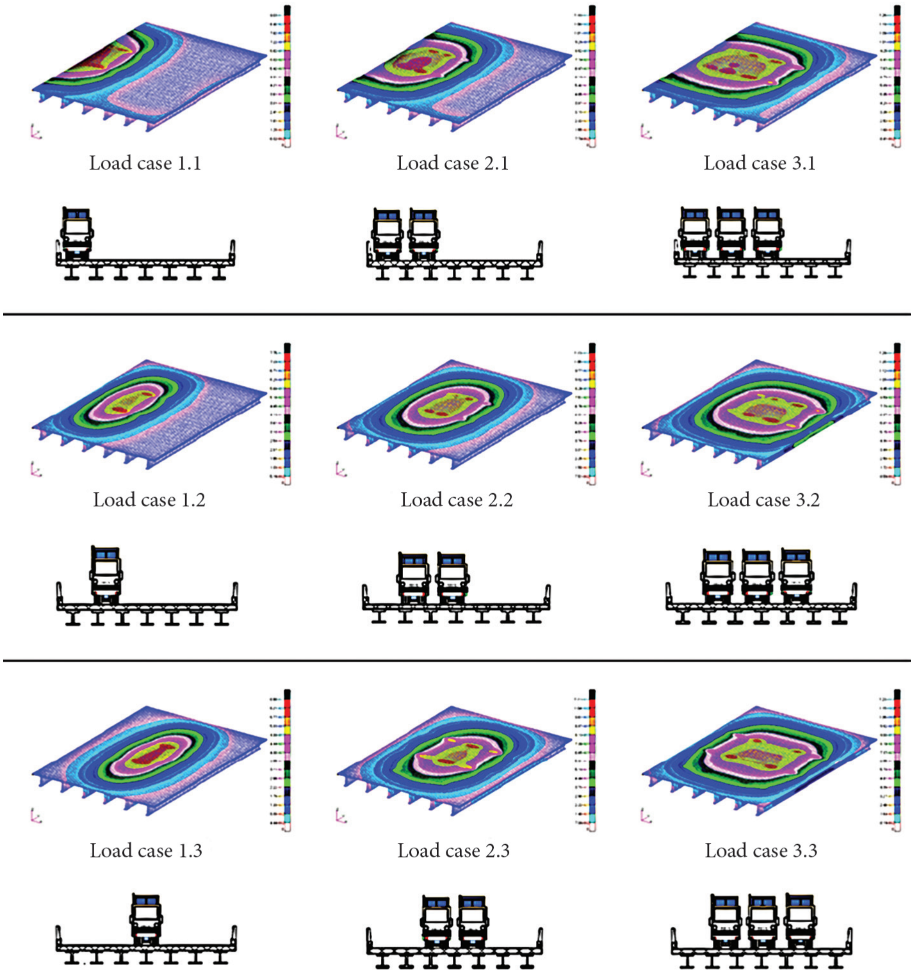


Fig. 5. Finite element models simulated by parametric study

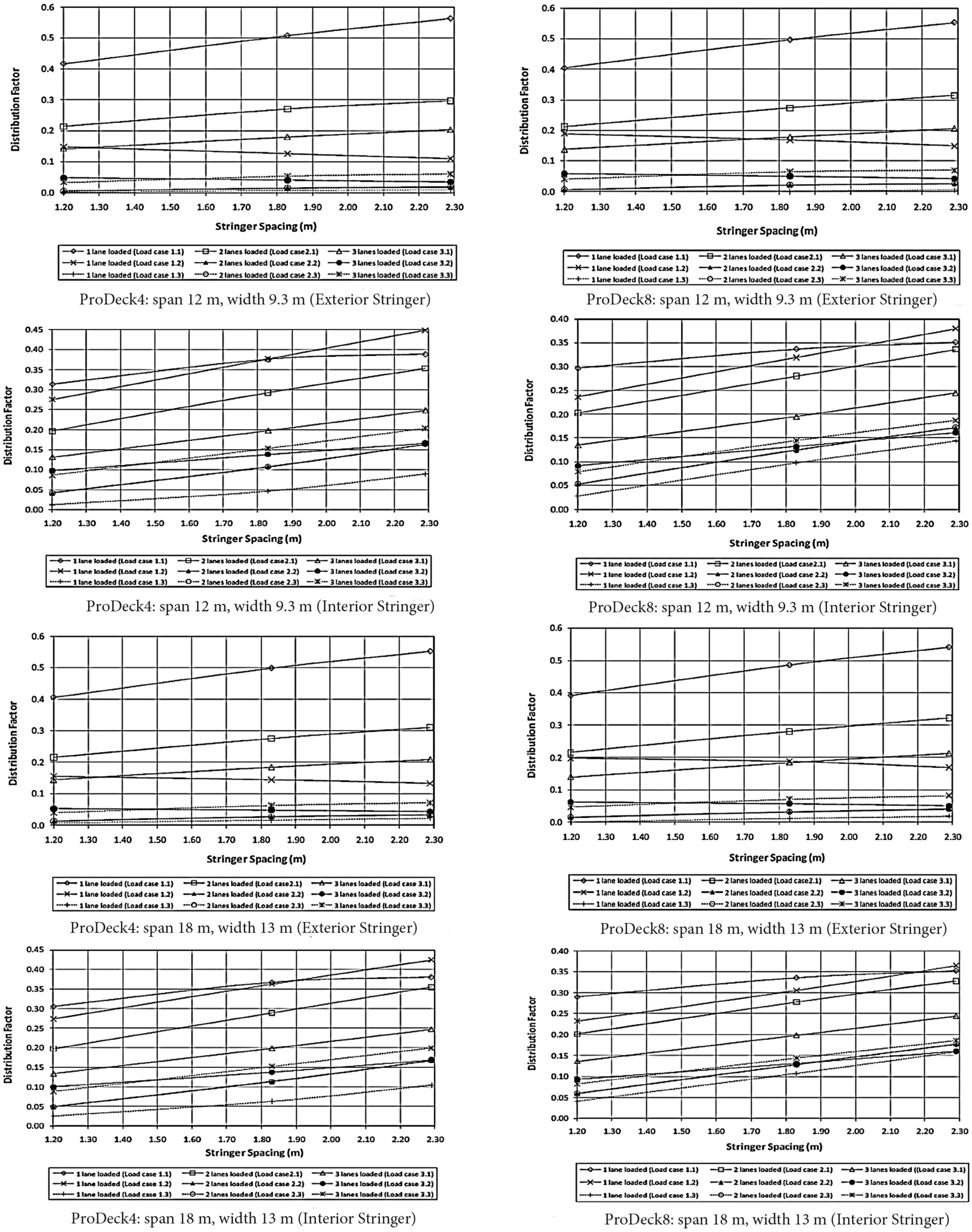
a simple and practical equation of the load distribution factor without loss in safety, the conventional form of the load distribution factor known as "*S*-over-factor" formula was generated using the analytical parametric data. The load distribution factors for interior and exterior stringers were proposed and presented in Table 4. The comparisons between the load distribution factors obtained from the present study and the standard specifications for highway bridges, 16^{th} and 17^{th} edition, American Association of State Highway and Transportation Officials are presented in Fig. 6. It was found that the load distribution factor equation from the standard specifications for highway bridges, 16^{th} edition, American Association of State Highway and Transportation Officials extensively overestimates the load distribution factors of FRP deck bridge models. In addition, the load distribution equation for 2 or more traffic lanes from the standard specifications for highway bridges, 17^{th} edition, American Association of State Highway and Transportation Officials provides the load distribution factors 12.8% to 51.1% higher than the load distribution factors from the parametric study.

However, the load distribution factors from the standard specifications for highway bridges, 17^{th} edition, American Association of State Highway and Transportation Officials are lower than these obtained from the parametric study for exterior stringers ($S < 1.5$ m). For 1-lane case, the load distribution factors from the standard equation are smaller than the load distribution factors from the parametric study through all spacing ranges in this study.

To correlate with the previous research data (Liu *et al.* 2008; Moses *et al.* 2006; Turner *et al.* 2004; Zhang, Cai 2007), the upper and lower bound covers all ranges of FRP deck bridges with steel stringer supports as shown in Fig. 7. The upper and lower bound values were developed to provide limited load distribution factors obtained from the available previous data. The upper bound of the load distribution factor is $0.1731S + 0.431$ and the lower bound of the load distribution factor is $0.1315S + 0.1026$. The upper and lower bound of the load distribution factors is based on the response of a few GFRP bridge decks as mentioned in this study. The different FRP deck systems will provide significantly different behaviour (Keller *et al.* 2004).

9. Conclusion

The present study has proposed the upper and lower bound values of the load distribution factors for the FRP deck-steel stringer bridge systems. The general and practical formula based on single parameter "*S*-over-factor"



ProDeck4: span 12 m, width 9.3 m (Exterior Stringer)

ProDeck8: span 12 m, width 9.3 m (Exterior Stringer)

ProDeck4: span 12 m, width 9.3 m (Interior Stringer)

ProDeck8: span 12 m, width 9.3 m (Interior Stringer)

ProDeck4: span 18 m, width 13 m (Exterior Stringer)

ProDeck8: span 18 m, width 13 m (Exterior Stringer)

ProDeck4: span 18 m, width 13 m (Interior Stringer)

ProDeck8: span 18 m, width 13 m (Interior Stringer)

Fig. 6. Load distribution factors for ProDeck 4 and ProDeck 8 – stringer bridge models

formula were developed using the finite element parametric study correlated with filed and analytical data of the previous researches. The results show that the load distribution factor formula based on the standard specifications for highway bridges, American Association of State Highway and Transportation Officials provides to be more or less conservative within the study range of stringer spacing. In addition, the use of the load distribution factors with various parameters is quite complex for ready implementation by many engineers. Therefore,

Table 4. Load distribution factors of FRP deck-steel stringer bridges

Researcher	FRP Deck Type	Steel Stringer			LDF	Methodology
		Size	Location	Spacing, m		
Luo (2003)	MMC	W24×104	Ext.	1.754	S/4.18	Field data
Tunner *et al.* (2004)	GFRP: Trapezoidal	W36×150	Ext.	2.440	S/5.55	Field data
Salim *et al.* (2006)	Honey Comb	W24×55	Ext.	0.686	S/2.93	Field data
Zhang, Cai (2006)	Honey Comb	W21×68	Int.	0.686	S/3.04	Laboratory testing Finite element
			Ext.	0.686	S/4.04	Laboratory testing Finite element
	Honey Comb	W36×232	Int.	2.29	S/3.53	Laboratory testing Finite element
			Ext.	2.29	S/5.61	Laboratory testing Finite element
Moses *et al.* (2006)	GFRP: Trapezoidal	W36×240	Ext.	2.847	S/4.29	Field data
		W24×104	Ext.	1.754	S/3.38	
		W36×150	Ext.	2.440	S/2.97	
Liu *et al.* (2008)	GFRP: Strongwell	W14×34	Int. Ext.	1.219	S/2.59 S/4.52	Laboratory testing
	GFRP: Strongwell	W24×99	Int. Ext.	1.829	S/2.81	Finite element
	GFRP: ProDeck 4	W24×104 W36×150	Ext.	1.20 1.83 2.29	S/2.86 S/3.58 S/3.89	Finite element
	GFRP: ProDeck 4	W24×104 W36×150	Int.	1.20 1.83 2.29	S/3.84 S/4.90 S/6.13	Finite element
	GFRP: ProDeck 8	W24×104 W36×150	Ext.	1.20 1.83 2.29	S/2.96 S/3,66 S/3.99	Finite element
	GFRP: ProDeck 8	W24×104 W36×150	Int.	1.20 1.83 2.29	S/4.02 S/5.35 S/6.55	Finite element
AASHTO (1996)	Concrete Deck	-------	Int.	-------	S/1.70	Standard specifications
AASHTO (2002)	Concrete Deck	Steel Stringer	Int.	S < 3.05	S/4.27	Standard (1-Lane)
AASHTO (2002)	Concrete Deck	Steel Stringer	Int.	S < 4.27	S/3.35	Standard (2 or more lanes)

Note: Ext. – exterior; Int. – interior.

the practical upper and lower limit of simplified load distribution factors based on single parameter "*S*-over-factor" without loss of accuracy are proposed. The present study supports the use of the proposed limits for guidance only in preliminary analysis and design. Other aspects of this study according to the modified load distribution factors based on LRFD design formulas are being studied and the results will be published as a sequel to this study.

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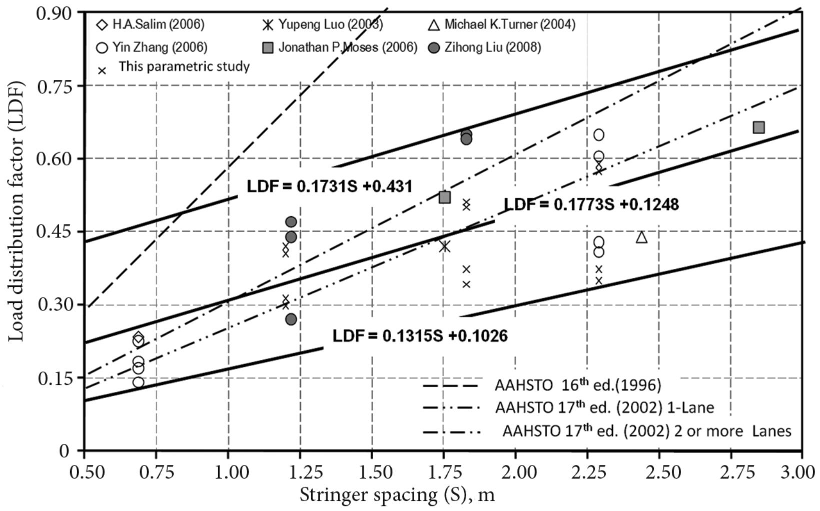

Fig. 7. Comparisons and correlation of load distribution factors with previous data

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