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REVIEW

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Full-scale test of precast prestressed concrete double-tee girder for rural bridges

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Abstract

Increasing the number of small and medium-sized bridges is a need to improve accessibility in rural areas of the Mekong River Delta of Vietnam. Many types of bridge structures can be the suitable selection for rural bridges, on which the overall load of the operating truck is about 100kN. An objective of this paper is to propose a double-tee (DT) girder with the span length varying from 12 m to 15 m for the rural bridge types B and C in the Vietnamese standard. New concrete aggregate using crushed sand and fly ash for the DT girders is also examined to solve the scarcity of natural sand and environmental problem from industrial waste. A full-scale DT girder with a span length of 12 m is tested to confirm the capacity of the proposed design. Result finds out that the concrete sand, which the natural sand is replaced by 90% of the crushed sand and 10% of the fly ash by weight, could be well applied for the proposed DT girders. Another finding is a linear elastic uncracked response of the tested DT girder under loads of a rural vehicle and concrete blocks of 306kN. Therefore, the proposed DT girders are suggested to the rural bridges.

Keywords: Double-tee girder, Prestressed concrete, Compressive strength, Flexural and shear capacities

1 Introduction

Many restrictions on the Mekong River Delta (MD)'s rural road system exist due to complex canal networks and creek flows (SIWRP 2011). Many rural bridges (Fig. 1), also known as monkey bridges, have been temporarily constructed for pedestrians and motorcycles. A recent study (World Bank 2016) shows that the MD area requires about 20,000 small and medium-sized bridges with span lengths ranging from 8 m up to 15 m for current traffic demand. For the last two decades, many rural bridges (Fig. 2) with a total width of 1.5 m to 2.5 m (World Bank 2016) have been built. These bridges are supported precast prestressed concrete girders with a legal truckload of 15kN to 35kN and a depth from 400 mm to 650 mm. However, these exiting bridges do not satisfy the rural bridge types B and C (TCVN-10380 2014), in which the legal truckload requires at least 60kN, and the bridge width is 4 m and 5 m, respectively. Some bridges, satisfied TCVN-10380 (2014) for the rural bridges, used precast prestressed I section concrete girders with cross-beams and concrete deck cast-in-situ (Fig. 3). This raises economic

Fig. 1 A monkey bridge

concern about the applicable structure since the economic span length of conventional I-section or T-section girders varies from 24 m to 33 m (AASHTO 2017). Furthermore, casting a deck in situ consumes a lot of time, which also increases the total cost for rural bridge construction.

Many types of prestressed concrete beams such as slab beam, void slab beam, spread slab beam, or double-tee (DT) girder could be applied for rural bridge types B and C. I-section beam, T-section beam, and spread slab beam exhibit more economical than slab beams, void slab beams, or box girders (Hueste et al. 2015). The NEXT (Northeast Extreme Tee) beam, developed by PCI Northeast (Singh 2014), with a span length from 15 m to 24 m has more advantages than I-section or T-section beams. Many bridges have been constructed by using the precast prestressed DT girders with their span length from 12.2 m to 18.3 m, and their depth of 584 mm (Rimal et al. 2021). Moreover, the spacing between stems of two adjacent DT girders is smaller than that between the stems of a DT girder, which decreases shear and moment transferring to the girders (Singh 2014; Rimal et al. 2021). The live load for the rural bridges is obviously smaller than that for the highway bridges, HL93 live load (AASHTO 2017). The distance among stems of the DT girder bridges could be the same to reduce the number of DT girders. Therefore, the DT girder bridges may save materials in comparison with bridges using spread slab beams, I-section beams, or T section beams, in consequence, to reduce the dead load. Reducing the dead load of bridges is preferable for a deep soft soil layer condition in the MD area (Truong et al. 2012). DT girder bridges also benefit from casting deck, safer construction by existing deck, and changing bridge width or skew bridge. For the aforementioned reasons, the prestressed concrete DT girder has been modified for the rural bridges considering the live load and bridge width, specified in TCVN-10380 (2014).

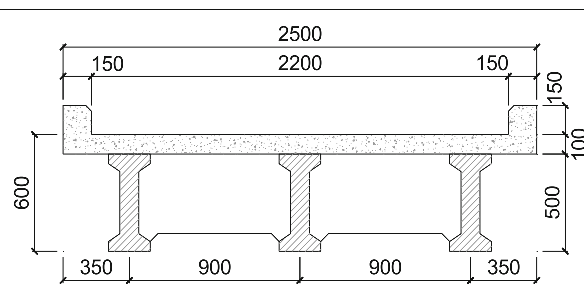
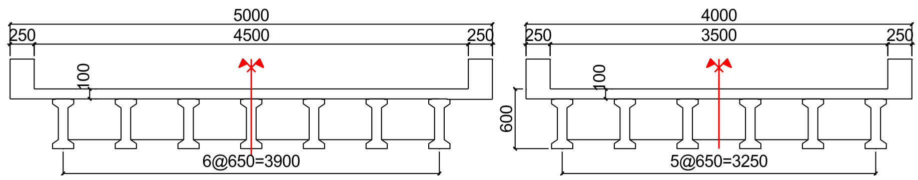


Fig. 2 A type of cross-section of rural bridges



(a) Bridge type B with a width of 5m (b) Bridge type C with a width of 4m

Fig. 3 Cross-sections of existing rural bridges using I section beams. **a** Bridge type B with a width of 5 m. **b** Bridge type C with a width of 4 m

Conventional concrete is a composite material composed of fine and coarse aggregate, cement and water. Fine aggregate often requires the fineness modulus (FM) from 2.4 to 3.0 (ACI 1991). Recently, the severe erosion of riverbanks has resulted in a shortage of sand for concrete. Using the crushed sand from stone (Makhloufi et al. 2014), ceramic waste (Li et al. 2021), or clay bricks (Chen et al. 2021) in replacement for the traditionally natural sand has been gaining popularity. However, the crushed sand has an angular shape that affects the workability and concrete quality. Water demand and cement paste content in the concrete using the angular crushed sand are generally higher than those in the conventional concrete (Makhloufi et al. 2014; Li et al. 2021). Admixtures such as the fly ash and superplasticizer are also added to improve the properties of concrete using the crushed sand. The compressive strength of concrete reduces with a replacement of the fly ash for the cement from 30% to 40% (Bentz et al. 2012). It is recently projected that the by-product of local thermal power plants is about 38.3 million tons in 2030, therefore, using fly ash for concrete also contributes to solving the environmental problems. High-strength concrete of 83 MPa was applied for the DT girder to increase its capacity (Maguire et al. 2013). However, the concrete strength of more than 60 MPa has been used for very few projects in the MD area, especially with cast-in-place concrete. The compressive strength of concrete (f'_c) for precast and prestressed concrete structures is generally from 34.5 MPa to 41.4 MPa (PCI 2010). Therefore, the concrete with compressive strength of 40 MPa is proposed to use for the DT girder in the design of the rural bridges in this project.

In this paper, the DT girders for rural bridges with the span length varying from 12 m to 15 m are proposed. HL93 live load in accordance with AASHTO (2017) with a reducing live load factor is taken into consideration. Maximum distribution factors are determined based on different typical cross-sections. Several concrete mixtures with the compressive strength of 40 MPa are examined by

Table 1 Specifications of designed live load and legal live load for rural bridges

Type of live load	Load (kN)			Wheelbase (m)
	Front axle	Rear-axle	Total live load	
Design truck	35	145	325	4.3
Tandem	110	110	220	1.2
Mitsubishi	18	46	64	3.35
T4081.YJ	23	56	79	3.8
HD3450A	30	61	91	3.23

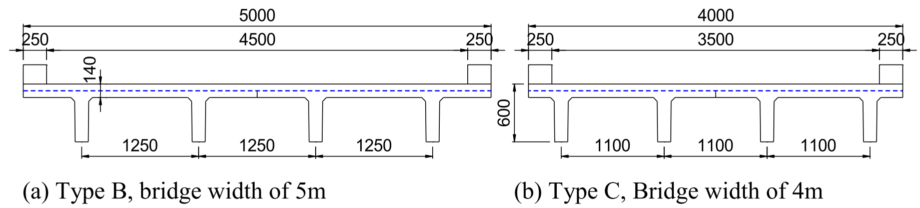


Fig. 4 Proposed cross-sections of rural bridges using DT girders. **a** Type B, bridge width of 5 m. **b** Type C, Bridge width of 4 m

some different proportions of sand, crushed sand, and fly ash. The preferable mixture is chosen for the design of the DT girders. A full-scale DT girder with the span length of 12 m is tested to validate the flexural and shear capacities of the proposed girder with loads of the rural legal vehicle and concrete blocks.

2 Design DT girder for rural bridges

2.1 Dimensions of DT girder

The length of DT girders from 12 m to 15 m is an appropriate choice for the rural bridges (TCVN-10380 2014). These span lengths fit with the width of popular canals and creek flows in the MD area. It also satisfies the clearance width allowance of 6 m (TCVN-10380 2014). A short span length reduces cross-section depth, dead load, and possibly transports the girders in the rural areas. The depth of girders, suggested in the TCVN-11823 (2017) that is referred from AASHTO (2017), is roughly 4.5% of the span length, therefore, it is taken as 600 mm.

Legal live load for the rural bridges is different from the legal trucks, given in AASHTO (2018). It usually includes two axles as a tandem, however, its axle load and wheelbase are different from those of tandem. Table 1 lists HL93 live load axle load (AASHTO 2017) and some legal vehicles in the rural areas (TCVN-10380 2014: Appendix C). Thus, the dimensions of bridge structures should be near the minimum range as suggested in the specifications (AASHTO 2017). Based on

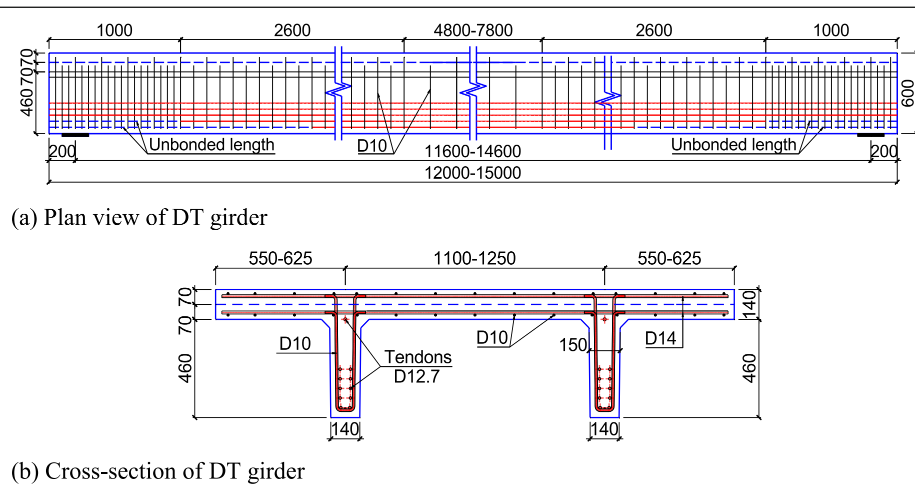


Fig. 5 Design DT girders. **a** Plan view of DT girder. **b** Cross-section of DT girder

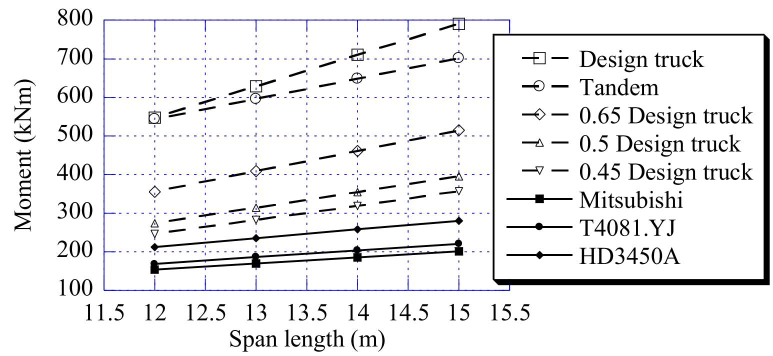


Fig. 6 A moment in the middle of girders under different live loads

TCVN-10380 (2014), the rural bridge types B and C are proposed with cross-sections using the DT girders (Fig. 4). Hence, the center to center spacing of two stems (s) of the DT girder is selected as 1250 mm and 1100 mm, which satisfy the AASHTO (2017) between 1100 mm and 4900 m. The minimum web width for reinforced concrete girder is 125 mm (AASHTO 2017). The web width ensures to carry the shear force and torsion, constructability, and protect the prestressing tendon from corrosion. So, the minimum stem width of the DT girder (t_w) is suggested as 140 mm.

The total top flange depth of the DT girder must satisfy Articles 5.14.1.5.1a and 9.7.2.4 in AASHTO (2017) as shown in Eq. (1) and Eq. (2):

$$t_{top} \geq \frac{s - t_w - 2t_h}{20} \quad \text{(Article 5.14.1.5.1a)} \tag{1}$$

$$6 \leq \frac{s}{t_{top}} \leq 18 \quad \text{(Article 9.7.2.4)} \tag{2}$$

where t_{top} is total top flange depth, t_h is the width of haunch. Based on the center to center spacing of 1100 mm, t_{top} calculated based on Eq. (1) is from 45 mm to 235 mm, while based on Eq. (2) t_{top} is from 60 mm to 270 mm. The minimum top flange depth to predict the distribution factor is 110 mm (AASHTO 2017). The top flange depth is also suggested to be not less than 175 mm for bridges using full HL93. The deck depth of existing bridges is 100 mm, where the center to center spacing between two girders is 650 mm (Fig. 2). In this study, the top flange depth of the DT girder of 140 mm is suggested. DT girders for the rural bridge types B and C are then designed (Fig. 5). The DT girder is separated into two parts of the precast and cast-in-situ. The depth of the precast part is 530 mm with a flange depth of 70 mm. The precast flange depth of at

Table 2 Methods to predict distribution factors for a one-lane load

Typical cross-section	Interior beam		Exterior beam	
	Moment	Shear	Moment	Shear
Type (*i*)	Lever rule	Lever rule	Lever rule	Lever rule
Type (*k*)	$0.06 + \left(\frac{S}{4300}\right)^{0.4}\left(\frac{S}{L}\right)^{0.3}\left(\frac{K_g}{Lt_s}\right)^{0.1}$	$0.36 + \frac{S}{7600}$	Lever rule	Lever rule

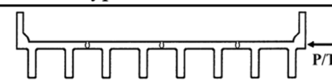
Supporting component	Type of deck	Typical cross section
Precast Concrete Double-Tee Sections with Shear keys and with or without Transverse Post-Tensioning	Integral concrete	

Fig. 7 Typical cross-section (*i*)

least 70 mm is constructability and reducing the dead load for transportation. The cast-in-situ part is 70 mm to unify the flange between two girders.

2.2 Reducing live load factor

The design live load for rural bridges includes two axles. Design truckload and axle load are not larger than 60kN and 25kN (TCVN-10380 2014), respectively. Reducing live load factor is decided by owners, but it is suggested by 0.50 or 0.65 for HL93, including lane load (TCVN-11823 2017). The maximum capacity of permitted vehicles in rural areas is 91kN, and its axle load is up to 61kN (Table 1). There is a high possibility, therefore, of overloading. The moment at the midspan of girders under different live loads in Table 1 shows in Fig. 6. The results show that span length from 12 m to 15 m design truck dominates compared to tandem. The moments by design truck with the reducing live load factor of 0.05 or 0.65 are much larger than those from operating trucks for rural bridges. The axle load of a design truck with a reducing live load factor of 0.45 results in 65.25kN, while the maximum axle load of operating trucks for rural bridges is 61kN. Therefore, reducing live load factor of 0.45 is suggested for the live load for rural bridges. Using smaller reducing live load leads to a decrease in the ultimate forces that could reduce the depth of the DT girder and the width of the stems, and increase the distance of the stems. Therefore, it results in reducing the materials, then reducing the construction cost of rural bridges.

2.2.1 Distribution factor

Distribution factors and lane load factor express live load acting on each girder. The widths of bridge types B and C are considered as one lane load. Thus, the lane load factor is 1.2 (AASHTO 2017). The distribution factor is classified into two types for moment and shear. The distribution factors (AASHTO 2017) for a DT girder are predicted based on the rules in Table 2 proposed for typical cross-section (*i*) (Fig. 7). However, the rules in Table 2 proposed for the typical

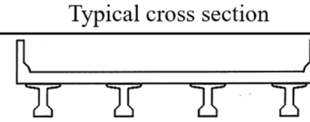
Supporting component	Type of deck	Typical cross section
Precast Concrete I or Bulb-Tee Sections	Cast in place concrete, precast concrete	

Fig. 8 Typical cross-section (*k*)

Table 3 Calculated distribution factors for one lane load

Typical cross-section	Span, *L* (m)	Spacing of stems, *s* (mm)	Distribution factor			
			Interior beam		Exterior beam	
			Moment	Shear	Moment	Shear
Type (*k*)	12	1100	0.337	0.505	0.409	0.409
	13		0.328			
	14		0.320			
	15		0.313			
Type (*i*)	12–15	2200	0.388	0.388	0.388	0.388
Type (*k*)	12	1250	0.364	0.524	0.340	0.340
	13		0.354			
	14		0.345			
	15		0.337			
Type (*i*)	12–15	2500	0.460	0.460	0.460	0.460

cross-section (*k*) (Fig. 8) could also be applied to calculate the distribution factors for a DT girder. In typical cross-section (*i*), the center-to-center spacing between two DT girders is used to calculate distribution factors. Meanwhile, using typical cross-section (*k*), the center to center spacing between two stems is used. In typical cross-section (*i*), the calculated distribution factor is separated equally into two stems. In typical cross-section (*k*), the factor is directly calculated to one stem. Table 3 tabulates distribution factors for one stem. Results show that the shear distribution factor is governed by the rules for the internal girder in typical cross-section (*k*), while the moment distribution factor is governed by rules for the internal girder in typical cross-section (*i*).

Each stem requires ten seven-wire low relaxation prestressing tendons type of 12.7 mm diameter Grade 1860 MPa to resist the ultimate moment. Table 4 lists materials for the bridges using the I-section girder (Fig. 2a) and DT girder (Fig. 4a), respectively. The result shows that the bridge with DT girders cuts off materials in comparison with I-section girders. Hence, proposed DT girders for the rural bridge types B and C are recommended.

3 Experiment

3.1 Materials

The compound materials and their properties are evaluated before the concrete mixture is selected for the DT girder. The maximum size of the coarse aggregate is 20 mm. Its unit weight and density (ASTM C128 2015) are 1398 kg/m^3 and 2.65 ton/m^3,

Table 4 Comparison of materials for rural bridges using I-section and DT girders

No.	Materials	Unit	Quantity	
			I section girder	DT girder
1	Concrete	m^3	17.1	16.1
2	Prestressing tendon type of 12.7 mm	ton	0.570	0.512
3	Normal reinforcing steel	ton	2.680	2.197

Fig. 9 Crushed Sand

respectively. The FM of natural concrete sand is 1.7 (ASTM C125 2015), while its unit weight and density are respectively 1478 kg/m^3 and 2.63 ton/m^3. The maximum size of crushed sand, the same rock to produce the coarse aggregate, is 4.75 mm (Fig. 9). FM of crushed sand is 3.0, and its absorption content is 1.42%. Fly ash (Fig. 10) is supplied from a local thermal power plant. The percentage of fly ash retained on a 45 μm sieve is less than 10%. The chemical composition of fly ash includes SO_3 (0.36%), Al_2O_3 (28.5%), SiO_2 (55.7), Fe_2O_3 (5.7%), and $Na_2O + 0.658K_2O$ (2.41%). Fly ash is classified as class F (ASTM C618 2015). The absorption content of fly ash is ignored in the mixture. The cement used in this study is PCB40, with its density of 3.15 ton/m^3.

The mixture C1 is determined based on ACI (1991) with a designed compressive of 40 MPa and sand with FM of 2.4. However, due to the natural sand scarcity with an FM of 2.4, the sand with an FM of 1.7 is employed in C1. Mixtures C2 and C3 are based on C1, in which 50% and 100% natural sand are replaced by the crushed sand by weight, respectively. Mixtures C4 and C5 are based on C3, in which the 10% and 15% crushed sand are replaced respectively by the fly ash by weight. All mixtures are listed in Table 5. Each compressive strength is an average reading of tested three-cylinder specimens (Table 6). Compressive strength on the 28th day of C1 is smaller than the

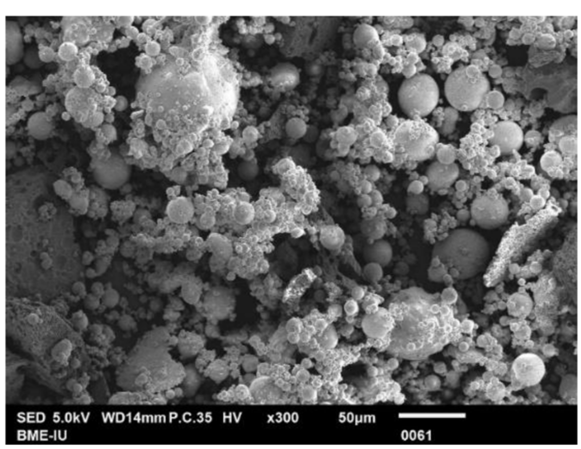


Fig. 10 Fly ash

Table 5 Mixture proportion for 1 m^3

Mixture	Coarse Agg. (kg)	Sand (kg)	Crushed sand (kg)	Fly Ash (kg)	Cement, C (kg)	Water. W (kg)	W/C	Super-plasticizer (kg)
C1	854	782	–	–	548	200	0.365	–
C2	854	391	391	–	548	200		5.5
C3	854	–	782	–	548	200		5.5
C4	854	–	704	78	548	200		5.5
C5	854	–	665	117	548	200		5.5

designed value. The compressive strength of C2 using the natural sand and crushed sand is higher than the design value. However, due to sand scarcity, mixture C2 is not chosen. Mixture C3 with fully crushed sand and without fly ash is also difficult to mix and place. Mixture C3 with the high slump shows close to segregation. Therefore, mixture C4, where 90% sand is replaced by the crushed sand, and 10% sand replaced by the fly ash by weight, is finally chosen for the testing DT girder. In mixture C5, replacing 15% natural concrete sand with fly ash is found to reduce the strength of concrete. It probably comes from the distribution of particle sizes of coarse and fine aggregates, and fly ash not to be optimum.

3.2 Testing

The full-scale DT girder of 12 m length had been tested in the construction site. Figure 1 shows the arrangement of reinforcing bars and prestressing tendons. The prestressing force is provided into tendons by a hydraulic jack before casting concrete (Fig. 1). After casting, concrete is cured within 6 days by providing water three times a day on covering jute bags (Fig. 1). The tendons are cut after 3 weeks, and the girder is tested after 4 weeks. Six-cylinder specimens are prepared to verify the compressive strength of concrete on cutting tendons and testing day. The compressive strength of concrete on the prestressing day and testing day is 41.3 MPa and 45.7 MPa, respectively.

Six pi-gauges are pasted continuously at the bottom fiber of the front stem to measure crack width (Fig. 1). Six displacement transducers, type of CDP-50 (Fig. 1), are set up at the bottom of the stems to measure the vertical deflection of the girder. Each pair of CDP-50s is located at locations of 5 m (D5), 6 m (the midspan, D6), and 7 m (D7). Two transducers, type of CDP-10, are also set up at the two bearings on the front stem (D0 and D12). All transducers and pi-gauges are connected to data logger TDS-630. There are two types of testing loads. A vehicle that

Table 6 Compressive strength of concrete mixtures

Mixture	Slump (cm)	Compressive strength, f'_c (MPa)		
		3 days	14 days	28 days
C1	12.5	–	–	32.84
C2	18.5	47.0	57.75	62.28
C3	22	24.9	35.67	44.73
C4	19	35.1	40.20	48.69
C5	19	20.9	22.65	30.57

Fig. 11 Normal reinforcing bars and tendons

is operated legally in rural areas is 102.1kN with a wheelbase of 3.25 m. The vehicle with the referring point from the rear axle moves toward and backward from 1 m to 8 m to collect data (Fig. 1). Concrete blocks weighing about 51kN each are another testing load. Concrete blocks are placed on two I-shape steel beams at the locations 5 m–7 m (location F5–7) to check the flexural capacity of the girder. Meanwhile, concrete blocks are located at locations of 9 m–11 m (location S9–11) and 2 m–4 m (location S2–4) (Fig. 1) to check the shear capacity. The order to place or remove concrete blocks is shown in Fig. 1.

4 Results and discussions

4.1 Crack pattern

During the testing vehicle moving toward and backward on the girder, no crack is observed by the naked eyes. The extension measured by pi-gauge is 0.02 mm. Distance between two legs of pi-gauge is 100 mm. The strain in concrete is subsequently calculated as 0.0002. Based on the cracking moment of the DT girder with considering prestressing force, the concrete strain corresponding to the cracking strength is calculated at about 0.00076. It means that the tested DT girder expects an elastic response under the load of the testing vehicle.

Fig. 12 Applying prestressing force

Fig. 13 External curing by wet jute bags

Until the applied load of 306 kN at location F5–7, no crack is observed by the naked eyes.

The 7th and 8th concrete blocks are craned continuously to create the applied load of 357kN and 408kN, respectively. At the applied load of 408kN, cracks are observed on both stems (Fig. 1). The occurrence of cracks is observed mainly between the two loading points. Loading is then stopped to avoid the complete failure of the girder so that the shear behavior of the girder could be validated in the next step. The crack width by pi-gauge at the 306kN is 0.1 mm that is a limit to protect steel from corrosion (Leonhardt 1988, TCVN-9346 2012), especially in tendons without duct. At the applied load of 357kN and 408kN, the maximum crack widths measured by pi-gauge are 0.25 mm and 0.39 mm, respectively.

No more new cracks are observed during the concrete blocks placed at locations of S9–11 or S2–4. At the applied load of 408 kN for the shear tests, the maximum crack width, which occurred during the flexure test, is observed by pi-gauge as 0.06 mm in the middle span. It seems that the DT girder also experiences the elastic response under the applied load for shear tests. After all concrete blocks are moved out, the crack width of 0.003 mm is still recorded by pi-gauge.

Fig. 14 Arrangement of 06 pi-gauges

Fig. 15 Setting up transducers

4.2 Relationship between load and deflection

4.2.1 Under vehicle load

Figure 20 shows the average deflection at D0, D5, D6, D7, and D12 when the testing vehicle moves forward on the DT girder. These behaviors are similar when the vehicle moves backward. The deflections at the same locations are very similar when the vehicle load moves forward or backward. When the vehicle moves out, the girder is back as the beginning. Therefore, the DT girder is considered working in the elastic stage. The maximum deflection at the middle DT girder when the vehicle moves forward and backward is 7.02 mm and 7.11 mm, respectively. The average maximum deflection of the middle girder is 7.06 mm. The allowable displacement of the prestressed concrete girder is 1/800 times of span length (AASHTO 2017), about 14.5 mm. The girder satisfies the deflection limit under an operated live load for rural bridges.

4.2.2 Under concrete blocks for checking the flexural capacity

Figure 2 shows the deflection of the DT girder under the load of the concrete blocks loaded as Fig. 1 at location F5–7. The deflections of the front and back stems are separated. The deflections recorded by the D5 and D7 are similar and smaller than that by the D6. When the first concrete block of 51kN is placed on the top of the front stem, the deflection of the front stem (FS) is higher than that of the back stem (BS). The maximum deflections of the front and back stems are 4.23 mm and 2.59 mm, respectively. When the second block is placed on the top of the back stem, the deflections of both stems are quite the same at 6.93 mm. This value is approximately equal to the average deflection by the 102.1kN-vehicle, 7.06 mm. Therefore, the DT girder is confirmed to be elasticity behavior under 100kN operated live load for rural bridges. The deflections of both stems

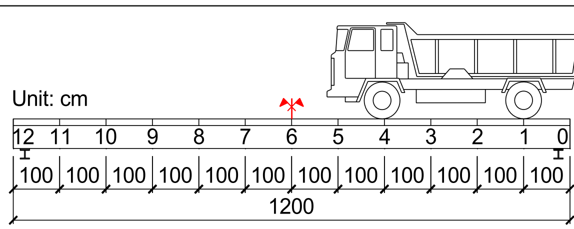


Fig. 16 Locations of the testing vehicle

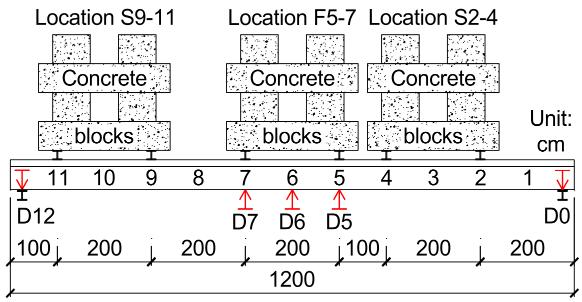


Fig. 17 Locations of blocks and transducers

are similar under the other concrete blocks. Because of the high stiffness of the concrete blocks, the applied load from other concrete blocks is distributed quite uniformly on the girder. The load and deflection relationships (Fig. 2) show a quite linear response until 306kN. The average deflection of the girder at the applied load of 204kN is 13.61 m. It means that the girder satisfies the deflection limit under the applied load of 204kN. The deflection has a larger increment when the applied load is increased up to 306kN and 408kN. At the same load level, the deflection of the girder in the unloading stage is larger than that in the loading stage. After moving all concrete blocks out, the residual displacement is observed (Fig. 2).

4.2.3 Under concrete blocks for checking the shear capacity

Figure 2 expresses the deflection of the stems when concrete blocks are on location S9–11. The deflection of the front stem is also larger than that of the back stem when the first concrete block is placed on top of the front stem. When other concrete blocks are placed, the deflections of both stems show similar behavior. Figure 2 shows relationships between the applied load and deflection at D7 or D5 when the applied load is located on locations S9–11 or S2–4, respectively. At the applied load of 408kN on location S9–11, the deflection of the girder at D7 is 14.4 mm. Meanwhile, at the applied load of 255kN on location S2–4, the deflection of the girder at D5 reaches up to 14.3

Fig. 18 Order of concrete blocks

Fig. 19 The crack pattern of the test DT girder

mm. The girder satisfies the deflection limit under the maximum applied load of 408kN and 255kN on locations S9–11 and S2–4, respectively.

4.3 Failure mechanisms

4.3.1 Flexural failure mechanism

A comparison between calculation and experiment deflections of the girder at the middle span under the load of the testing vehicle is conducted (Fig. 2). The result shows that the experimental results are in good agreement with the calculated results. The difference of the deflection at the middle span of the girder between the experimental result and calculation result under the load of the testing vehicle is from 0.1% to 4.2%. It also confirmed the elastic behavior of the tested girder under the testing vehicle load.

The behavior of a girder is normally separated into 3 stages: linear elastic uncracked stage, linear elastic cracked stage, and nonlinear cracked stages (Nguyen 2010; Nguyen 2011). The crack width obtained by pi-gauge at the applied load of 255kN was 0.06 mm. The tensile strain in concrete is 0.0006 which is smaller than the strain of 0.00076. At the applied load of 306kN, the measured crack width is 0.1 mm or a strain in the concrete of 0.001. Crack width is, however, not observed by the naked eyes at 306kN. Figure 2 shows the comparison of calculation and experiment deflections of the girder at the middle span under the applied load at location F5–7. The results show that the calculation results entirely captures the

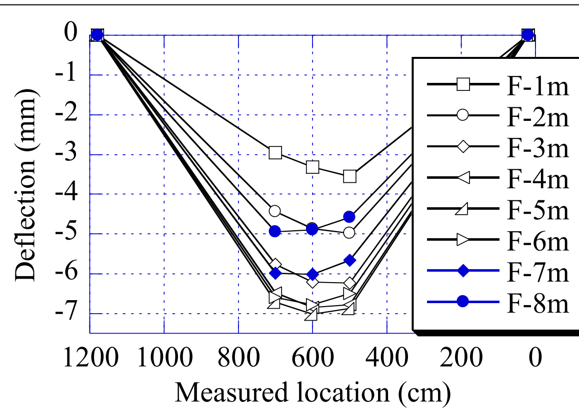


Fig. 20 Deflection of the girder when the vehicle moved forward

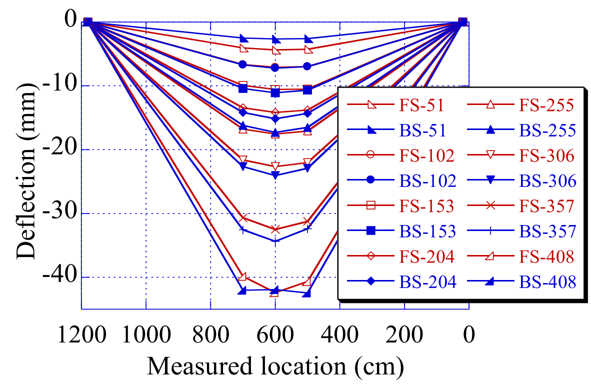


Fig. 21 Deflection of stems under concrete blocks at location F5–7

experimental results from the beginning until 306kN with a linear response. After 306kN, the observed deflections of the tested girder are larger than the deflections from the calculation. The reason is that the occurrence of crack from the applied load of 306kN reduces the stiffness of the cross-section.

From 306kN to 408kN, the slope of the load and deflection curve shows a smaller value than that in the linear elastic uncracked stage. At the applied load of 408kN, concrete strain at the bottom fiber is 0.0039, crack width of 0.39 mm, which is much larger than 0.00076. Therefore, concrete is in the post-peak tension region. The girder is considered in a linear elastic cracked stage from 306kN to 408kN. The ultimate flexural capacity is not examined because of stopping an applied load. However, flexural cracks tend to propagate into the compression zone with an increment of crack width, the failure mechanism of the girder could be considered as a flexural failure mode. A load of 306kN considered as the end of the linear elastic uncracked stage is almost three times higher than the operated truck for rural bridges, about 100kN. Therefore, the flexural capacity of the test girder could resist the moment under operated live load for rural bridges.

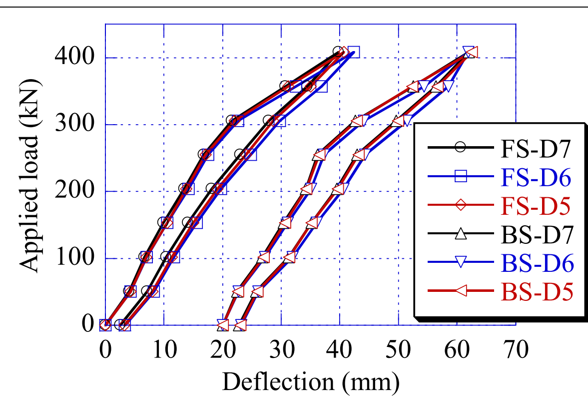


Fig. 22 Applied load and deflection curve at location F5–7

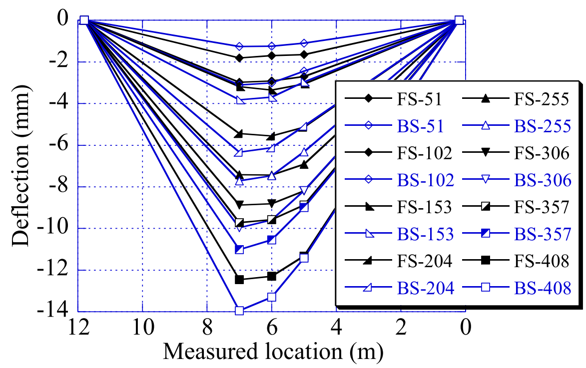


Fig. 23 Deflection of stems under concrete blocks at location S9–11

4.3.2 Shear failure mechanism

The load and deflection curves of the tested DT girder (Fig. 2) show quite linear until 408kN as the applied load is on locations S9–11 or S2–4. At the applied load of 306kN at location S9–11, the load of the first crack in the flexure test, the reaction force at the left bearing is calculated as 258.5kN, twice larger than truckload for rural bridges, about 100kN. When four concrete blocks (204kN) are located on both locations S9–11 and S2–4, the recorded deflection at the middle span and crack width are 18.1 mm and 0.03 mm, respectively. Considering linear response under the applied load 204kN on both locations S9–11 and S2–4, the calculation deflection of the girder is 17.3 mm that is approximately equal to the experimental deflection. Thus, the DT girder shows linear elastic uncracked stage behavior under an applied load of 204kN on both locations for checking shear. It could be confirmed that the tested DT girder has enough shear capacity to resist two operated vehicles of 100kN under the linear stage.

The shear failure mode of the DT girder depends on the tensile stress of concrete and stirrup, yielding stirrup before crushing web concrete, inclined flexure-shear crack, or inclined web-shear crack. The nominal shear capacity of the DT girder (AASHTO 2017) at sections of 9 m (or 3 m) and 4 m is predicted in Table 7. Base on the calculation, flexure-shear failure mode is predicted dominance.

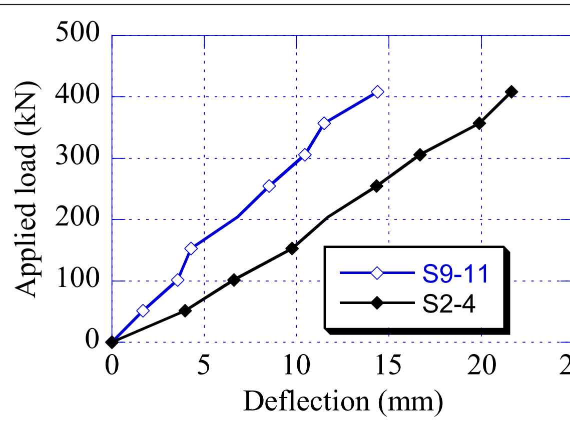


Fig. 24 Load and deflection curve at locations S9–11 and S2–4

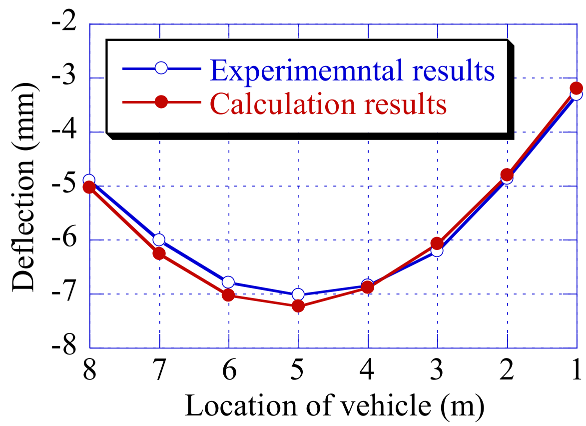


Fig. 25 Deflections from calculation and experiment under vehicle load

5 Conclusions

Many types of bridge structures can be applied for rural bridges where the operating truck is about 100kN. This paper, precast prestressed DT concrete girder with span length varying from 12 m to 15 m is designed and suggested for rural bridge types B and C. Based on the design and experimental results, the following conclusions are made:

- Tested DT girder also saves materials compared to the existing prestressed I beam bridge.
- Reducing live load factor of 0.45 is suggested for HL93 live load for rural bridges in design.
- The distribution factor for the shear is governed by the rules for the internal girder in the typical cross-section (*k*), while the distribution factor for the moment is governed by the rules for the external girder in the typical cross-section (*i*).
- Due to the lack of natural sand, the natural concrete sand in the concrete mixture is replaced by 90% of crushed sand and 10% of fly ash in weight. Its compressive strength tested at 28 days in the laboratory and construction site for the tested DT girder is 48.69 MPa and 45.7 MPa, respectively. This mixture could be well applied for DT girders for rural bridges.

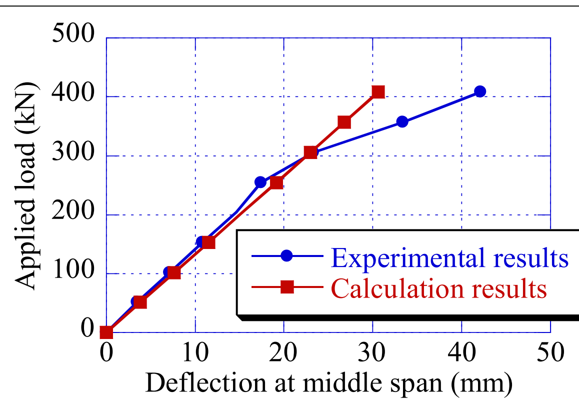


Fig. 26 Deflections from calculation and experiment under concrete blocks

Table 7 Shear capacities of DT girder predicted based on AASHTO (2017)

Section	Tensile stress of concrete and stirrup (kN)	Yielding stirrup before crushing web concrete (kN)	Inclined flexure-shear crack (kN)	Inclined web-shear crack (kN)
9 m (or 3 m)	1332	1349	1042	1678
4 m	1084	1546	998	1403

- Experimental results of the DT girder with the span length of 12 m show a linear elastic uncracked response under the load of the testing truck at all the testing locations and until the load of the concrete blocks of 306kN. The DT girder could be estimated to fail in the flexural failure mode under the flexural test and the flexural-shear failure mode under shear testes. The DT girder has enough flexural and shear capacities to resist live load for rural bridges, about 100kN. The proposed DT concrete girders could be applied to rural bridges.

Abbreviations

AASHTO: American Association of State Highway Officials; ACI: American Concrete Institute; ASTM: American Society for Testing and Materials; DT: Double Tee; FM: Fineness Modulus; HL93: Highway Load accepted in 1993; MD: Mekong River Delta; PCI: Precast/Prestressed Concrete Institute; SIWRP: Southern Institute for Water Resources Planning; TCVN: Vietnam Standards, abbreviated TCVN for the Vietnamese

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Not application.

Authors' contributions

Dinh Hung Nguyen raised the idea, designed DT girders, experimented, analyzing data and writing the original draft, Hong Nghiep Vu verified the design, participated experiment and helped to draft the manuscript. Thac Quang Nguyen participated experiment, helped to draft the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

All data and materials in their manuscript can be applied publicly.

Declarations

Competing interests

The authors declare that they have no competing interests.

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