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Flexural Behavior of Concrete-Filled Steel Tube Members and Its Application

Jae-Yoon Kang[1,*], Eun-Suk Choi[2], Won-Jong Chin[2] and Jung-Woo Lee[2]

[1]*Senior Researcher, Structural System Research Division, Korea Institute of Construction Technology, Korea*
[2]*Researcher, Structural System Research Division, Korea Institute of Construction Technology, Korea*

Abstract

The concrete-filled steel tube (CFT) member has many advantages compared with the ordinary structural member made of steel or reinforced concrete. One of the main advantages is the interaction between the steel tube and concrete: concrete delays the steel tube's local buckling, whereas the steel tube confines the concrete and thereby increases the concrete's strength. A new bridge system described in this paper uses concrete-filled steel tubes as replacement for conventional girders. The composite bridge system with the CFT girder is compatible with restrictions on girder height, is relatively easy to build, and is resistant to seismic forces by their good durability and deformability. In this paper, we evaluate the practical application of this new type of CFT girder. It includes experimental investigations of the flexural behavior of concrete-filled steel tubes, which varies depending on the strength of the filling material. We also evaluated their application as continuous girders. Test results showed that concrete-filled steel tube girders have good ductility and maintain their strength up to the end of the loading. Results of this investigation demonstrated the potential of the concrete-filled tube as a bridge girder.

Keywords: concrete-filled steel tube, CFT, CFT girder bridge, composite action

1. Introduction

A concrete-filled tube (CFT) member consisting of a steel tube filled with concrete material realizes the importance of steel reinforcement to provide confinement for the concrete and to increase the load-carrying capacity of the composite member. In particular, CFT members have a number of distinctive advantages over conventional steel-reinforced concrete members, and they are widely used for structures that require a great applied moment and ductile deformation. It provides excellent seismic resistance and good damping characteristic. It also exhibits good hysteresis under cyclic loading. From the structural point of view, the concrete filling in the steel hollow section not only prevents the occurrence of the steel's local buckling but it also enhances the ductility of the CFT member up to the ultimate load. All of the above phenomena are mainly due to the structural interaction between the inner concrete and the outer steel tube. When load is applied to the CFT member, the concrete inside the steel tube lies in a tri-axial state due to the steel tube's confining effect on the concrete's volume changes. This confining by the steel tube provides lateral compressive pressure on the concrete inside it. It is commonly known that the strength of concrete in the multi-axial compressive state is much higher than its strength in the uni-axial loading condition.

Recently, the utilization of CFT member has been expanded to bridge structure as a girder member. A steel/concrete composite railway bridge system using CFT girders was developed and constructed in Japan (Hosaka *et al.*, 1997; Nakamura *et al.*, 2004). For this new structural concept of bridge, two kinds of composite actions are taken into account in relation to bending moment, shown in Fig. 1; the contribution to the flexural resistance of the concrete filling is not considered in the region of the positive flexure as the tensile stress works. The steel tube girder in this region is filled with ultralight mortar for reduced weight. The ultralight mortar, so-called air mortar, is a new product that is produced by mixing air bubbles with cement milk. Its unit weight can be less than 10 kN/m^3, with a compressive strength that varies from 0.4 to 10 MPa by controlling air volume. On the contrary, in the negative flexural region, the composite action of the concrete filling is considered, and the lightweight concrete is filled (Mastumura *et al.*, 2003; Nakamura *et al.*, 2004).

In this paper, we present an experimental investigation of the flexural behavior of circular CFT beams subjected to pure bending. We examine the strength and ductility of the CFT member constructed from cold-formed steel tubes filled with plain concrete or air mortar. The failure

*Corresponding author
Tel: +82-31-910-0135; Fax +82-31-910-0121
E-mail: jykang@kict.re.kr

modes of hollow and CFT members under pure bending are compared. And, for the practical utilization of the confining effect in bending, a new type of sectional arrangement for the CFT girder was suggested. Also, in this paper, we introduce an innovative bridge system using CFT member as bridge girder under flexural behavior. The innovative composite bridge system proposed in this paper can utilize most of the advantages of structural components and reduce construction cost.

2. Experiments on Flexural Behavior of the CFT Member

2.1. Influence of compressive strength of void filling material

In case of CFT member subjected to bending load, the concrete core does not stay under the triaxial state of stress, and the section of concrete core is separated into the compressive and tensile zones by neutral axis. However, the composite action between the steel tube and concrete still controls the enhancement of the CFT member in structural properties by the delay of the steel shell's inward buckling.

In this study, the flexural behavior of the CFT according to the compressive strength of the in-filling material was investigated by a four-point bending test as shown in Fig. 1. Design parameters for test specimens are shown in Table 1. Load-deflection curves obtained by the experiments are shown in Fig. 2. In the B00-N-N specimen, after the steel yielded, the curve became nonlinear by the spreading of the plastic area. When the applied load reached the maximum, the steel plate in compression at the top buckled and the applied load sharply decreased. However, there was a considerable increase in the bending strength and ductility of BCF-N-N over the hollow tube. The bending strength of the BCF-N-N was 1.5 times higher than that of the B00-N-N. Severe local buckling at the compressive side is not observed for this specimen. The model BMF-N-N filled with air mortar behaved similarly to the hollow tube, B00-N-N, during the early stage of loading. In case of the BMF-N-N, however, the applied load still continued to increase up to 1.2 times the peak load of the hollow tube, and the buckling shape was shallower than that of the hollow tube. It means that the filled concrete played an important role in restricting or delaying the local buckling of the steel pipe and increased the pipe's ductility and bending strength. It is understood by the test results of the BMF-N-N that this confinement effect can be expected when the filling material has low strength.

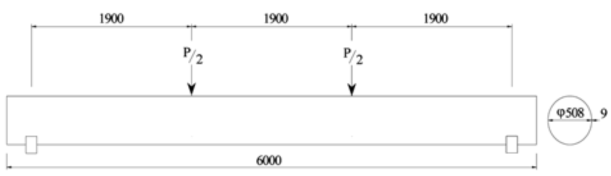
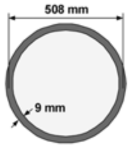


Figure 1. Four-point bending test setup.

Table 1. Test specimens (SS400, fy = 360 MPa, D/t = 56.4)

Specimen	Filling material	Mechanical interlock	Steel tube
B00-N-N	-	-	
BCF-N-N	Plain concrete (f_{ck} = 27 MPa)	Friction only	
BMF-N-N	Air mortar (f_{ck} = 8 MPa)	Friction only	

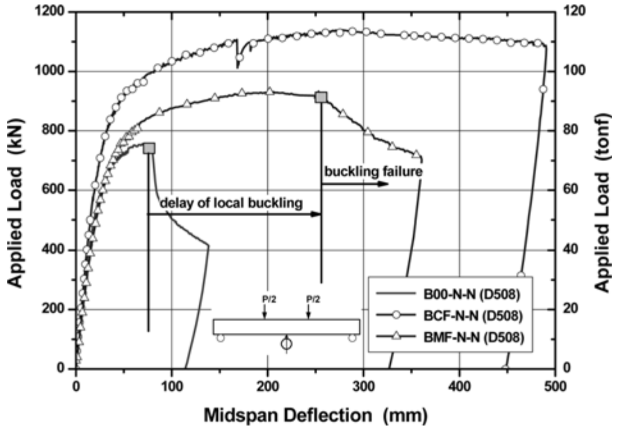


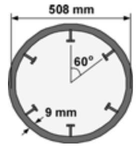
Figure 2. Load-deflection relation in the bending test.

2.2. Influence of mechanical interlocking

The bending resistance and flexural behaviour of the CFT member with mechanical interlocking devices was experimentally investigated to understand the effect of the enhancement of the composite action between the steel shell and the in-filling material. The steel tube used for the construction of the specimens was 508 mm in diameter and 9 mm in thickness. Two kinds of specimens, BCF-6P-N and BMF-6P-N, were filled with plain concrete and air mortar, respectively, and had six ㄱ-shaped perfobond ribs in a regular angle of 60^{o} inside the steel tube as shown in Fig. 3. These ㄱ-shaped perfobond ribs were applied to intensify the composite action of the steel tube and core concrete. The specimen was simply supported with a span of 5.7 m and loaded at two points 1.9 m from the end supports.

Fig. 4 shows the results of the bending test carried out for specimens, BCF-6P-N and BMF-6P-N, with inner ribs. For specimen BCF-6P-N, the bending strength was

Table 2. Test specimens (SS400, fy = 360 MPa, D/t = 56.4)

Specimen	Filling material	Mechanical interlock	Steel tube
BCF-6P-N	Plain concrete (f_{ck} = 27 MPa)	ㄱ-shaped perfobond rib	
BMF-6P-N	Air mortar (f_{ck} = 8 MPa)	ㄱ-shaped perfobond rib	

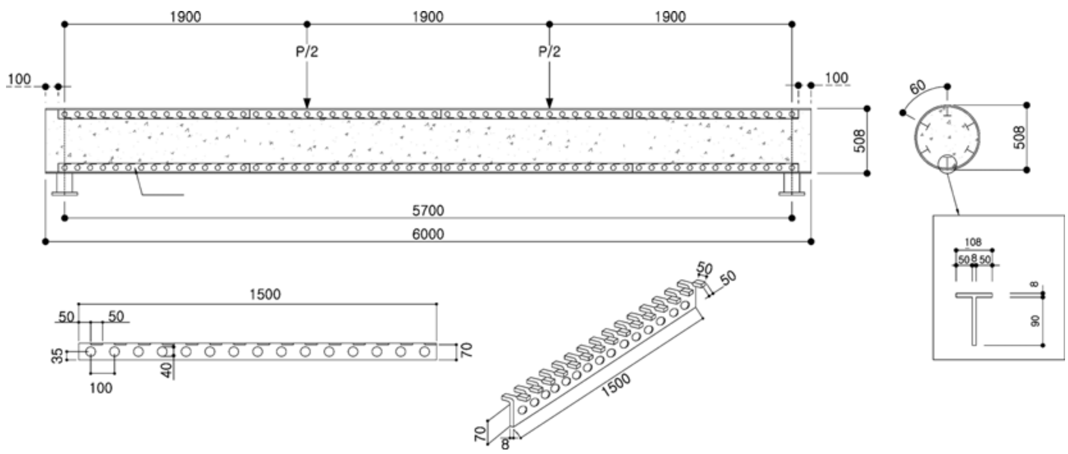
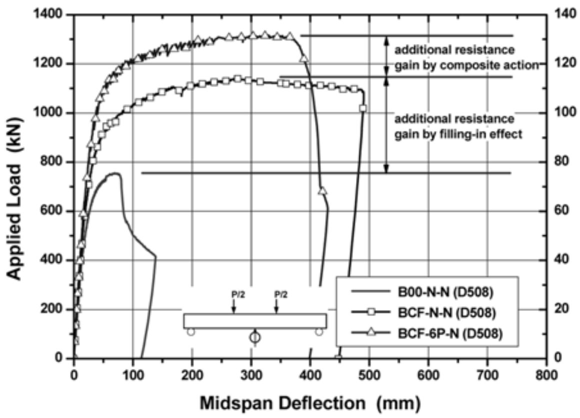
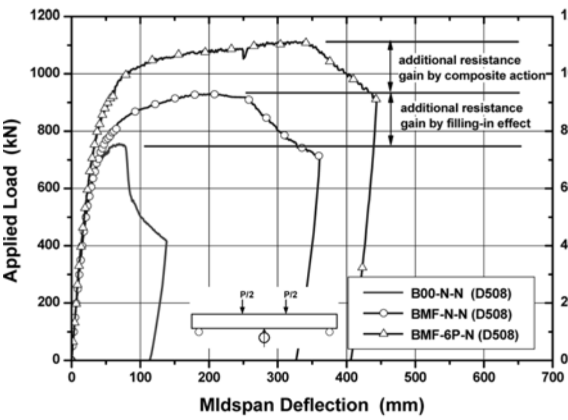


Figure 3. Sectional view of specimens with interlocking devices.



(a) Specimens filled with concrete



(b) Specimens filled with air mortar

Figure 4. Load-deflection curves of specimens with inner ribs. (a) Specimens filled with concrete (b) Specimens filled with air mortar.

1.7 and 1.2 times higher than that of B00-N-N and BCF-N-N, respectively. The bending strength of specimen BMF-6P-N was 1.5 and 1.2 times higher than that of B00-N-N and BMF-N-N. These results suggest that, by introducing a mechanical device arranged in the steel tube to fortify the composite action, the bending strength

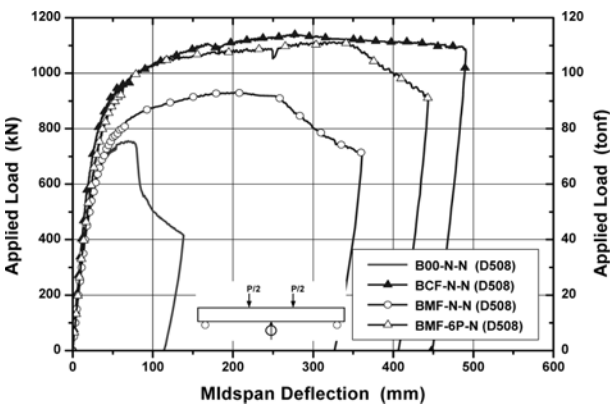


Figure 5. Load-deflection curves of the CFT girder.

of the CFT member can be enhanced. These results suggest that introducing a mechanical device arranged in the inner side of the steel tube to fortify the composite action can enhance the bending strength of the CFT member. Especially, as shown in Fig. 5, it is worth noting that the bending strength of BMF-6P-N increased up to the same level of the bending strength for BCF-N-N; it is concluded, thereby, that the bending strength and ductility of a steel tube filled with low-strength material can be controlled by installing shear key for the enhancement of the bond between the steel tube and core material.

3. Application of the CFT as bridge girders

3.1. Concept of CFT girder composite bridge system

A new steel/concrete composite bridge system has been proposed using steel pipes as the main girders, as shown in Fig. 6. Steel pipes are produced at steel mills to reduce the amount of the welding process and fabrication expenses. Pipe girders are filled with different concrete materials depending on the flexural behavior; the pipe girder near the intermediate support is filled with normal concrete, whereas it remains un-filled around the span-center or it is filled with air mortar to reduce its weight. Air mortar

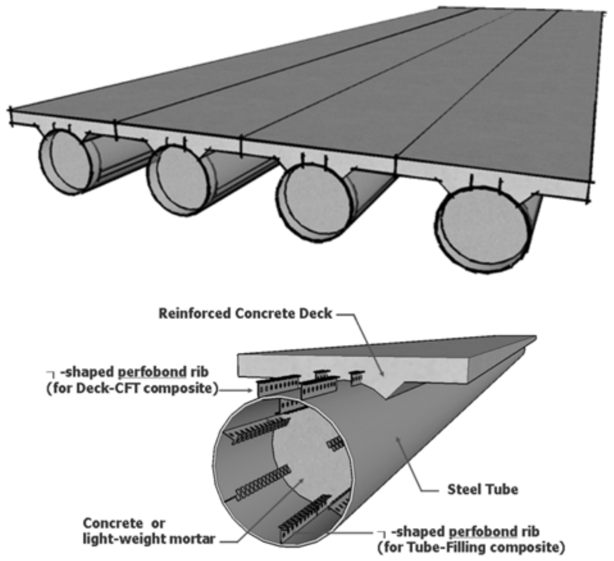


Figure 6. Concept of the CFT girder bridge system.

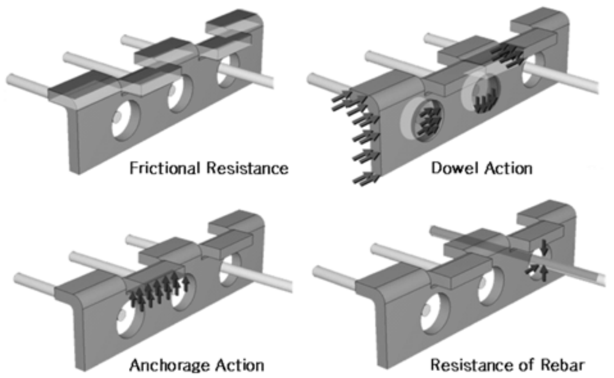


Figure 7. Resistance mechanism of ㄱ-shaped perfobond rib connector.

is a lightweight aerated mortar with a density of as low as about 1.0. In this study, the ㄱ-shaped perfobond rib was considered as a shear connector to improve the composite action of the CFT girder and RC deck. This type of perfobond rib, as shown in Fig. 7, has a folded flange on the top of the web to increase shear resistance by expansion of the surface area. Flange parts, by its anchorage action, prevent the pull-out of the rib connector from the concrete deck under flexural behavior, which is the main problem with the conventional perfobond rib connector proposed by Leonhardt (Leonhardt *et al*., 1987).

3.2. Flexural behavior of the CFT girder-RC deck composite section

To examine the behavior of the continuous span bridge with CFT girder, the loading test for the two-span continuous span bridge specimen was conducted. Design parameters for the specimen were the in-filling condition in the positive moment section and condition for the composite action between the tube and the core. The steel tube's diameter was 508 mm, and thickness was 9 mm. The span length of the test specimen was 7.4 m, and the total length of test specimen was 14.8 m. A length of 4.8 m in the negative moment section in the mid-support was filled with concrete with a compressive strength of 21 MPa. Test specimens can be classified into two kinds according to the in-filling condition of the positive moment section VOID specimen, which was not filled in positive moment section, has diaphragms to prevent the ovalization of the void section: MORT and MORP specimens were filled with air mortar. The MORT specimen secures the composite action between the tube and core by natural friction, whereas mechanical interlocking devices of the ㄱ-shaped perfobond rib were installed for the MORP specimen, as shown in Fig. 8.

As in the test result, the load-deflection relationship is shown in Fig. 9. For the VOID specimen, the ultimate load per actuator reached up to 1757.0 KN, and it produced a negative moment of 2535.9 kN · m in the section of the mid-support. In case of specimens filled with air mortar in the positive moment section, MORT and MORP, the maximum negative moment was 2533.8 kN · m and 2726.3 kN · m, respectively. Consequently, both the VOID and MORT specimens had an almost similar load-carrying capacity; however, that of MORP relatively increased by up to 7.5%.

In case of loading test for the continuous span bridge, the structural behavior of VOID and MORT specimens was not different despite the great difference in the in-filling condition in the positive moment section: hollow and solid. This phenomenon seems to be due to fact that the flexural stiffness of the negative moment section was dominant for the overall structural system where the section was filled with concrete in the same condition. Moreover, the neutral axis in the positive moment section lay near the top side of the tube; therefore, the compressive strength of the core material, which is in the tensile stress state, did not contribute to the strength of the composite section. On the contrary, in case of the MORP specimen, the flexural stiffness of the composite section increased and was affected by the composite action of the tube and core and intensified by the mechanical interlocking device.

From the experimental results, it was known that the in-filling condition and the tube-core composite action govern the structural behavior of the continuous span bridge. Also, the material property of the core material in the positive moment section has a minimal influence on the flexural stiffness of the composite section. Consequently, in case of continuous span bridge structures, the flexural behavior of the CFT girder can be controlled according to the strength of the in-filling core material and the length of the CFT member in the mid-support. For the positive moment section, there are several alternatives to the design, such as installing a diaphragm as stiffener of the hollow tube or filling the tube with lightweight material.

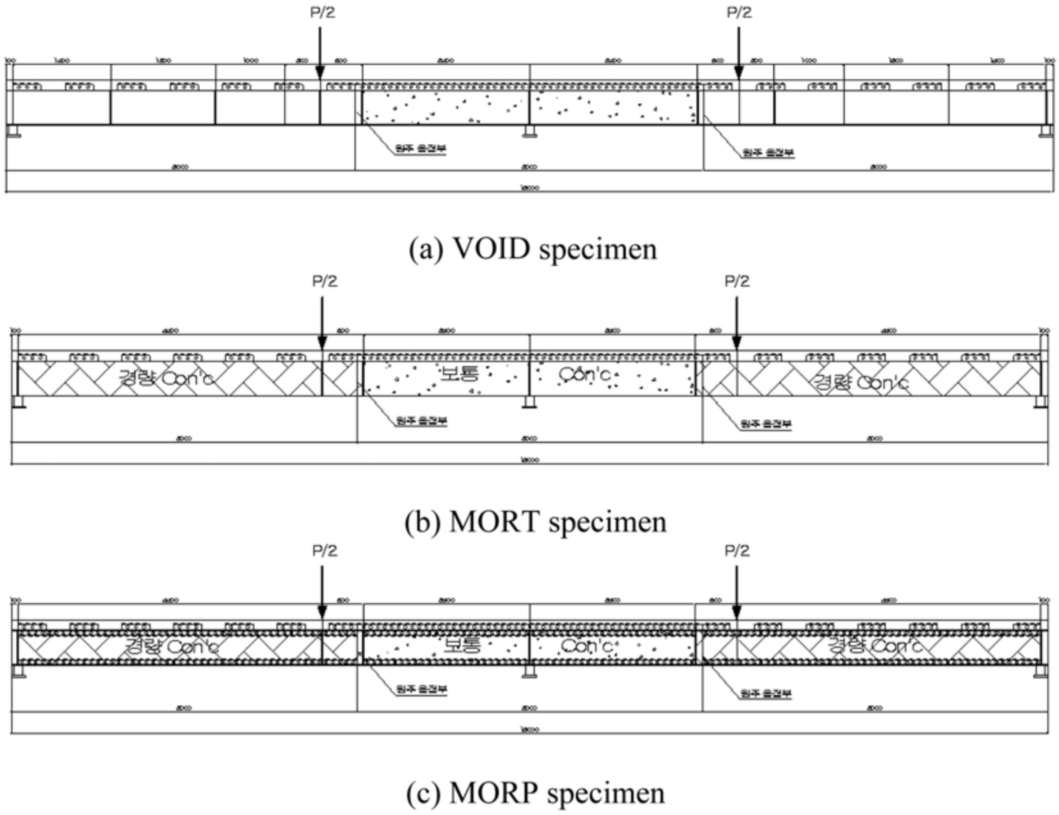


Figure 8. Test specimens for the two-span continuous CFT girder bridge.

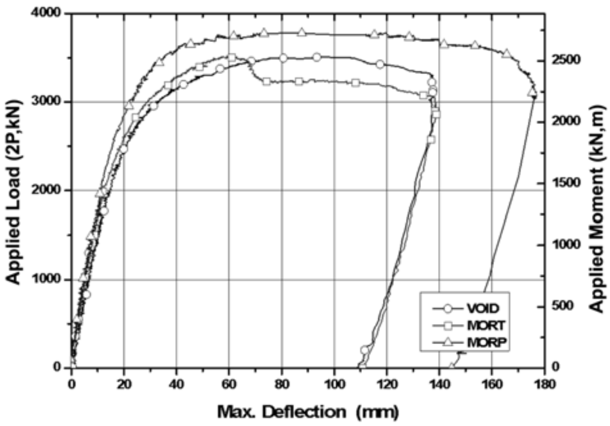


Figure 9. Load-deflection curve for two-span continuous CFT girder bridge specimens.

4. Conclusions

In this study, we proposed a new steel/concrete composite bridge system with steel pipes girders filled with concrete as the main girders. This type of bridge can entail a substantially reduced amount of welding and a consequently lower fabrication cost. Considering the advantages offered by CFT members, such as remarkable bearing capacity, excellent deformability and inhibition of noise and vibration, in this study, we examined alternatives to its use as a girder in the structure of a bridge and performed experimental investigation to develop a new type of steel composite bridge. Accordingly, scaled-down prototype tests were conducted to investigate the flexural behavior of the CFT member. Based on the results, the composition of an economical girder section was determined so as to maximize the advantages of the CFT member and secure its efficiency as bridge girder. The following conclusions can be derived from the results of the bending tests carried out on the CFT girder bridge.

- Concrete filling prevents the local buckling of the steel shell, and it also contributes to the inertia of the section and internal forces, which increases the flexural strength and stiffness of the member.
- The introduction of a mechanical device contributing to the composite action between the steel tube and filling material and controlling the bond failure at the interface made it possible to obtain large flexural resistance. In such a case, the performance of the CFT girder could be secured even with low-strength filling material.
- Especially, in the case of filling with low-strength filling material, if both composition effect and stiffening effect can be achieved simultaneously through the use of ㄱ-shaped perfobond ribs as composition connector, flexural resistance similar to the one developed using ordinary concrete could be obtained.
- The use of the newly developed ㄱ-shaped perfobond shear connector to combine the slab and the CFT girder could secure the perfect composite behavior of the

section until the maximum load, with a more remarkable sectional resistance and ductility than those of previous stud-type shear connectors.

- The CFT girder was seen to be the most effective structure in the negative moment section, which provides the support under the compressive stress state. It also seemed advisable to continuously build two or three spans in order to produce an economical design and fully exploit the structural advantages of the CFT girder steel composite bridge.

Acknowledgment

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