

정적 시험을 사용한 CFTA거더의 제조시 강성 결함 탐색

Detection of Manufacturing Defects in Stiffness of CFTA Girder using Static Loading

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요 지

새로운 형태의 교량 거더인 CFTA(Concrete filled and tied tubular steel arch) 거더의 비선형 거동에 대해 고찰한 후, CFTA 거더의 대량 공장 생산시 콘크리트 충전 불량으로 발생할 수 있는 결함인 거더 안의 빈 공간을 탐지하는 새로운 방법을 제안하였다. CFTA 거더 안의 비대칭성 콘크리트 충전 불량 결함을 구조물의 대칭 거동을 이용하여 탐색하였으며, 수치해석과 실험을 통해 제안된 방법을 검증하였다. 제안된 방법을 수치적으로 검증하기 위해 3차원 유한요소모델을 사용하였으며, 실험적으로 검증하기 위해 CFTA거더의 정적 실험자료를 사용하였다.

핵심용어 : CFTA 거더, 정적재하, 제조결함, 대칭성

Abstract

This paper presents a study on the nonlinear behavior of an innovative bridge girder made from concrete-filled and tied tubular steel arch (CFTA) under static loading. Manufacturing of the CFTA girder may have defects which may highly affect the symmetry and performance of the structure. A simple method is proposed by using stiffness extracted from static test data to detect manufacturing defects of the CFTA girder. A three-dimensional finite element model was used in the numerical analysis in order to verify the method. The proposed method was experimentally validated through static tests of the CFTA girder. The application of the proposed method showed that it is effective in identifying invisible manufacturing defects of the CFTA girder, especially for mass production of a standard type in the factory.

Keywords : CFTA girder, static loading, manufacturing defect, symmetry

1. Introduction

Concrete filled tubular steel(CFT) structure is a typical steel-concrete composite member, which has high load-bearing capacity and other good structural performances, such as high ductility and energy dissipation ability, due to the composite action between steel and concrete in the member(Lu *et al.*, 2009). CFT constructions have advantages over whole steel tube members and reinforced concrete

members. The in-filled concrete delays local buckling of the steel tube and the steel tube reinforces the concrete to resist tension, bending moment, and shear force. The tube also acts as a formwork for the concrete during construction of the bridge, thus saving a major construction cost (Roeder *et al.*, 1999; Varma *et al.*, 2002). The high tensile strength and ductility of the steel component can be utilized using CFT with the advantages of compressive strength and stiffness of concrete(Trung *et*

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et al., 2008; Jeong *et al.*, 2009; Roh *et al.*, 2011). As steel plates are combined with concrete, the resistance against buckling increases and eliminating heavy stiffening, which make composite bridges more economical and competitive compared to a typical concrete bridge. In addition, the steel/concrete composite bridges are lighter, guarantee better quality and have easier and faster erection than conventional concrete bridges (Chaudhary *et al.*, 2007; 2009, Choi, 2008; Chou, 2008). The composite bridges are also expected to reduce noise and vibration levels and are therefore environmentally friendly (Nakamura *et al.*, 2002). The CFT structural members have a number of distinctive advantages over conventional steel reinforced concrete members. CFT members provide excellent seismic resistance in two orthogonal directions as well as good damping characteristics (Elchalakani *et al.*, 2001). CFT has high resistance against bending moments and compressive axial forces and are ideal as arch ribs (Nakamura *et al.*, 2008). The steel tube not only takes axial load, but also provides confining pressure to the concrete core, while the concrete core takes axial load and prevents or delays local buckling of the steel tube (Huang *et al.*, 2002).

In this study, a new type of bridge girder is discussed that can maximize the structural efficiency by combining CFT structure, arch structure, and pre-stressing structure. The type of girder is called concrete-filled and tied tubular steel arch (CFTA) that can be made to long span with light weight. It is structurally stable with small amount of material and maintenance. The CFTA bridge girder has many advantages compared to the typical bridge girder structures because it makes use of almost all the prominent characteristics of each material and structural design, including buckling prevention by concrete filling, a higher stiffness and durability due to the confinement effect, a longer span and lighter structure due to pre-stressed tendons, as well as the pleasing aesthetics of an arch shape (Lee *et al.*, 2008). In addition, this bridge girder has a good resistance to reduce the moment by ways of an arch

shape and pre-stressing force and to induce compressive force to compensate for tensile stress.

The CFTA girder should be produced in mass in the factories, since field construction is not available. However, the manufacturing defects, e.g. the voids between filled concrete and steel tubular, have a significant effect on the symmetry and performance of the structure. It may be noted that the defect due to voids is not visible as compared to the defect in other types of structures. In this paper, a methodology to quantify the manufacturing defects of CFTA and nonlinearity of the structure is presented by using stiffness data extracted from simple static loading tests. Finite element (FE) analysis and static loading tests on a real CFTA bridge girder model were performed to validate the proposed method. The proposed method seems to have potentials in verifying manufacturing defects of CFTA girder, especially in case of mass production of the standard type in the factory.

2. Description of the structure

The bridge under consideration is a composite system of CFTA bridge girder that consists of a steel surface, concrete arch, tendons, and concrete deck components. In order to transfer the self-weight of concrete to the arch rib after manufacturing the steel surface of girder with arch shape, column concrete is filled so that the composition of steel and concrete is completed with empty space inside of steel surface. In addition, the pre-stressed tendons which are located in the lower part of composite girder ends are installed to compensate loads effectively. This bridge with the span of 25.6m is located at Korea Institute of Construction Technology (KICT), Ilsan, SouthKorea. The tubular steel arch is composed of steel plates with different thicknesses, among which, the thickness of the middle part of each top and lower flange is 22mm, the thickness of steel plate cover at the end of the girder until the middle part of flanges is 12mm, and the thickness of each side of the girder is 10mm. The slab is 3.5m in width and 0.24m in

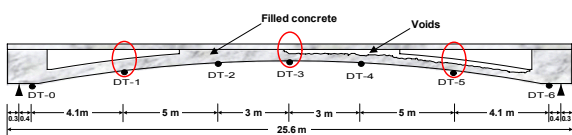
thickness. The edges of girder are connected by 4 pre-stressed tendons in the longitudinal direction, with cross section area of 1664.4mm². The cross section of girder is 1.5m in width and 1.5m in depth.

3. Detection of manufacturing defects in the girder

Manufacturing defects may cause the structure unsafe and usually are invisible, in which void is one of the main defects in the stiffness change. One of the engineering challenges is filling the complex steel tubes with concrete without any voids to make the structure more efficient. Fig. 1 shows the voids inside and along the CFTA girder that existed during pouring of the concrete into tubular steel.



(a)



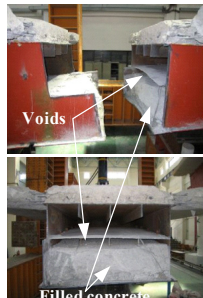
(b)



(c)



(d)



(e)

Fig. 1 CFTA girder: (a) Overview, (b) Schematic of girder with voids, (c)–(e) Experimental defect model at location DT-1, DT-3 and DT-5

The voids have a significant effect on the static behavior of CFTA girder and symmetry of structure as well. There are many factors that affect on the presence of the voids inside the girder such as the density of filled concrete and the shape of the girder.

The stiffness calculation is utilized to detect the voids inside CFTA girder as following:

$$K_{DT-n} = \Delta F_n / \Delta u_n \quad (1)$$

where K_{DT-n} is the stiffness at each measured point, $n=1,2,3,\dots$ is the number of load steps, ΔF is the difference between each sequence load and Δu is the difference between displacements with the same position at each load step.

The method to detect voids of the structure is presented in order to determine the manufacturing defects. In other words, this method is important to verify the integrity of the structure after construction in order to localize the voids inside the girder. The procedure to perform the detection is based on the difference of stiffness between the first and last load steps or total stiffness for all load steps at each measured point as given in the following equations:

$$\Delta K_{DT-n} = (F_n - F_1) / (u_n - u_1) \quad (2)$$

$$\Sigma K_{DT-n} = K_{DT-1} + K_{DT-2} + \dots + K_{DT-n}$$

where ΔK_{DT-n} is the difference between the high and low stiffness, F_1 and F_n are the first and last load steps respectively, u_1 and u_n are the displacements extracted from the first and last load steps respectively and ΣK_{DT-n} is the summation of stiffness for all load steps.

4. Numerical simulation

4.1 Finite element modeling

The 3D FE model of the CFTA bridge was constructed using the structural software Strand7, which involve four main components as shown in

Fig. 2. It may be noted that there is hollow space holding the concrete inside the steel tubular, which can create a very efficient composite section. For the pre-stressed tendons, two inside tendons have 883.61MPa pretension stress and two outside tendons have 443.82MPa pretension stress. The FE model of the bridge is composed of 6560 solid elements, 3668 shell elements, 12 beam elements and 9243 nodes. Table 1 shows material properties of the CFTA girder model. Analytical displacements of the corresponding nodes at the same monitored points with the test specimen were obtained by static analysis.

To simulate the nonlinear behavior of the CFTA bridge girder, the stress-strain curves for concrete and slab are used. All empirical equations available to predict the stress-strain curves proposed by Ahmed *et al.* (1982) are used here to determine the stress-strain characteristics for slab and filled concrete, which can be represented by the following equations:

$$\sigma_1/\sigma_{p(1)} = \frac{A_1 \frac{\varepsilon_1}{\varepsilon_{p(1)}} + (D_1 - 1) \left(\frac{\varepsilon_1}{\varepsilon_{p(1)}} \right)^2}{1 + (A_1 - 2) \frac{\varepsilon_1}{\varepsilon_{p(1)}} + D_1 \left(\frac{\varepsilon_1}{\varepsilon_{p(1)}} \right)^2} \quad (3)$$

where A_1 and D_1 are parameters that describe the ascending and descending parts of the stress-strain curve. They are given as follows:

$$A_1 = \frac{\varepsilon_0}{\varepsilon_{sp(1)}} \quad (4)$$

$$E_{sp1} = \frac{\sigma_{p(1)}}{\varepsilon_{p(1)}}$$

$$D_1 = 1.111 + 0.876A_1 - 0.4 \times 0.883 \times \tau_{oct}/f'_c$$

where E_0 and $\sigma_{p(1)}$ are as defined previously, $\varepsilon_{p(1)}$ is the axial strain at the stress state $\sigma_{p(1)}$, and $E_{sp(1)}$ is as given by $E_{sp} = E_0/[1+4(A-1)x]$ with $A = E_0 \times \varepsilon_0/f'_c$. The octahedral shear stress is given by $\tau_{oct} = \sqrt{2J_2/3}$.

The compressive stress-strain curve for FE analysis is defined using Eq. (3). In order to

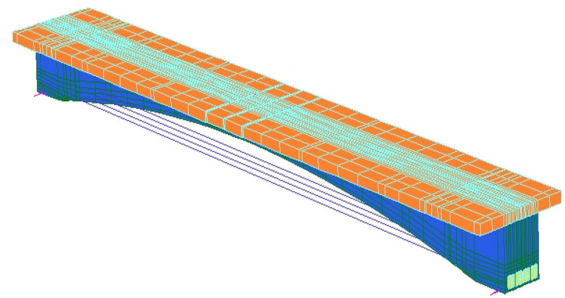


Fig. 2 Numerical model of the girder

Table 1 Material properties of bridge

| Component | Density (kg/m ³) | Young's Modulus(MPa) | Poisson's Ratio |
|-----------------|------------------------------|----------------------|-----------------|
| Slab | 2500 | 18800 | 0.167 |
| Filled concrete | 2500 | 27223 | 0.167 |
| Steel plates | 7850 | 210000 | 0.3 |
| Tendons | 8000 | 210000 | 0.3 |

specify yield stress, the Chord method (Kosteski *et al.*, 1999) is conducted. Figs. 3 and 4 show the stress-strain curves of filled concrete and slab, respectively. The maximum FE stress for filled concrete and slab are lower than the yield stress, which proves that the FEM analysis is in the

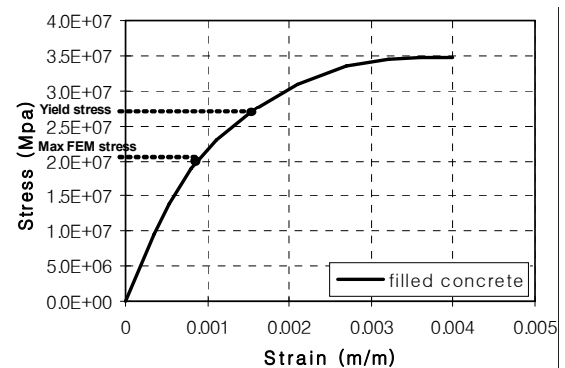


Fig. 3 Analytical stress-strain diagram of concrete

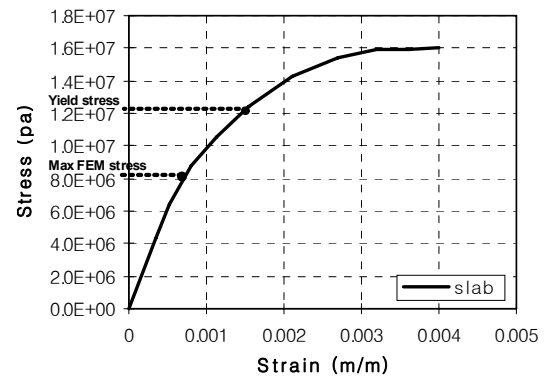


Fig. 4 Analytical stress-strain diagram of slab

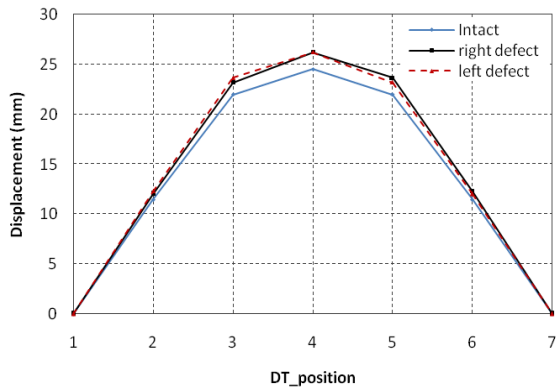


Fig. 5 Analytical displacement curves for intact, right defect and left defect FEM

elastic range.

To show the performance of the proposed method, three analytical models with different locations along the girder are estimated, among which the first model is intact model, the second model considers the voids located in left side and the third model considers the voids located in right side of girder. From those three models the displacements are extracted by applying 298kN as the maximum load and they are compared as shown in Fig. 5. The displacement curves of the defect model show that the deflection at defect side is higher than the intact side. And the intact model shows the symmetry behavior with less deflection and higher stiffness. Since the intact model is available in numerical simulation, the symmetric defects of the girder can be detected by comparing with the intact model.

4.2 Manufacturing defects detection

Eq. (1) is used to calculate the numerical stiffness from FEM as shown in Fig. 6, from which one can note the reduction of stiffness at each point with the increasing load step proves the nonlinear behavior of the CFTA girder.

The numerical verification procedure is performed by applying the nonlinear static analysis for each intact and defective FE model. The intact FE model is represented by the tubular steel fully filled with concrete and the defective FE model is conducted by removing some elements from the left part of

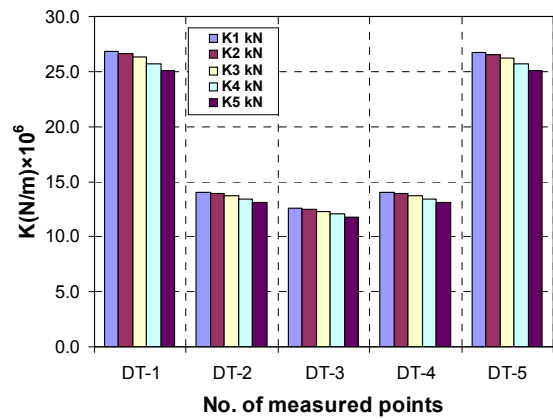


Fig. 6 Numerical stiffness at measured points

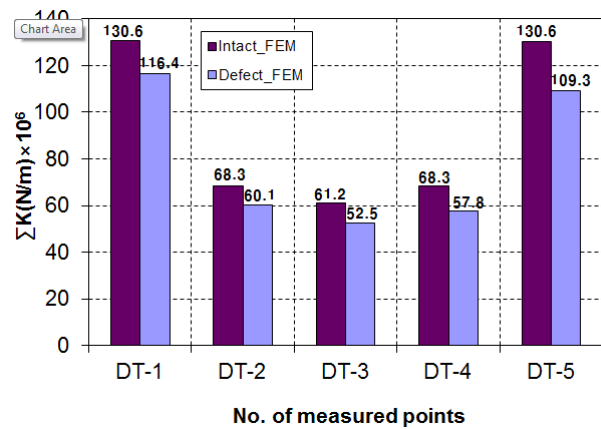


Fig. 7 Comparison of intact and defective FE models

CFTA girder. Fig. 7 shows the numerical results of total stiffness for intact and defective FE models. The comparison shows that the proposed method is effective in detecting the manufacturing defects of the CFTA girder.

5. Experimental study

In order to specify the static behavior of CFTA girder, a prototype was constructed and tested. According to the design guidelines, the most important parameter that has to be measured during the experimental test is the vertical displacement of the bridge, especially until service load by taking consideration of the requirement of the guidelines for a maximum permissible deformation (Giannopoulos *et al.*, 2003). The vertical displacements were measured at five locations along the specimen by seven displacement transducers. The numerical displacements

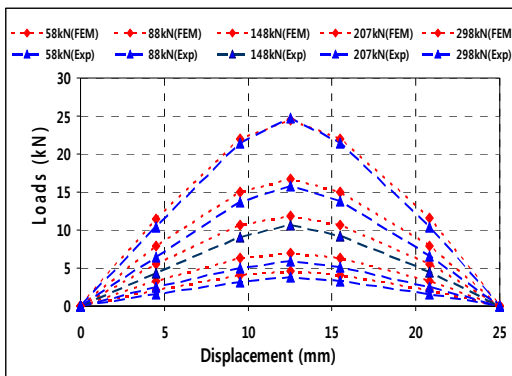


Fig. 8 Comparison of experimental and numerical displacements

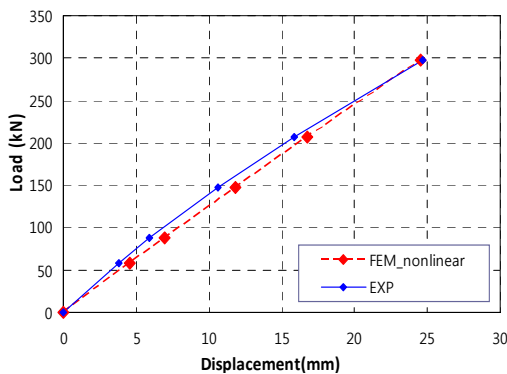


Fig. 9 Comparison of displacements at middle point

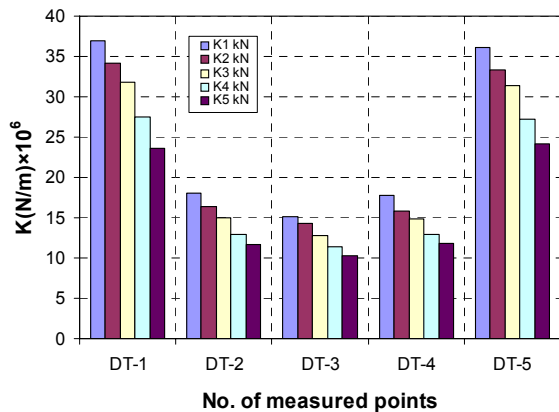


Fig. 10 Experimental stiffness at measured points

were simulated from the FE model considering the same location of displacement transducers in the experimental test. Fig. 8 shows the comparison between the experimental and numerical displacements. It can be observed from Fig. 9 that the displacement of the real structure is in close agreement with the one calculated from the finite element analysis. The nonlinearity of CFTA girder increases as the load step increases.

Fig. 10 shows the stiffness reduction at each

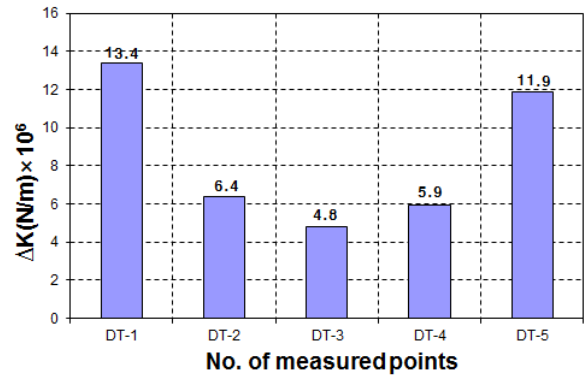


Fig. 11 Experimental stiffness differences

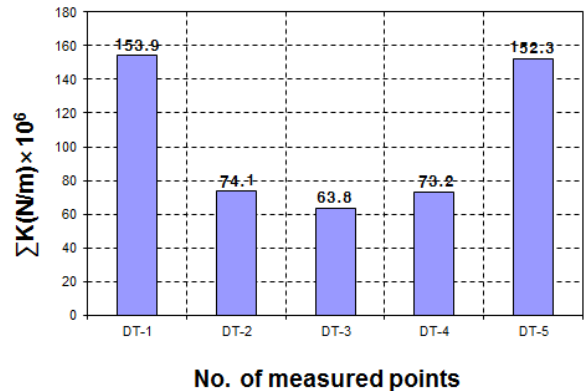


Fig. 12 Total experimental stiffness for all load steps

measured point with the increasing load step and the nonlinearity of structure. Fig. 11 shows stiffness difference at measured points of the experimental model, from which one can note that the girder is asymmetric and the right side of girder is weaker than the left side. Fig. 12 shows experimental results of the total stiffness of all load steps at each measured points. It demonstrates that it is possible to detect the voids inside CFTA girder by using Eq. (2).

6. Conclusions

In this paper, a method for detection of manufacturing defects in the CFTA girder is presented using static loading. An FE model has been presented in order to simulate the behavior of the structure and to be used in the future for the design of similar structures. The FE model was utilized to verify the proposed method for manufacturing detection in this study. The stiffness at each

measured point is calculated in order to localize the voids inside the girder and to verify the integrity of the structure after construction. Both the numerical analysis and the experimental study showed that the proposed method can detect the voids inside the CFTA girder during the construction in the factory effectively. The proposed method seems to have potentials in detection of manufacturing defects of CFTA girders in case of mass production of the standard type in the factory, where the data of the intact model can be used for comparison of results and for identifying the manufacturing defects by using static loading.

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