DIFFERENTIAL CAMBER INDUCED STRESSES IN SHEAR KEYS IN DECKED BULB TEE (DBT) GIRDER BRIDGES

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ABSTRACT

Recently, accelerated bridge construction (ABC) has become more widely popular. Prefabricated bridge elements in ABC are usually produced under controlled environmental conditions off site, transported to the construction site, and assembled together using different types of connections. Decked bulb tee (DBT) girders are considered a promising system for ABC. Adjacent DBT girders are placed side by side and connected together along longitudinal joints. The longitudinal joint connections can consist of weld plates or headed bars and grouted shear keys. However, differential camber between adjacent girders, especially in skew bridges, could cause an issue during construction. Various leveling procedures have been implemented to minimize the differential camber between adjacent units such as jacking, surcharging, and crane-assisted leveling. However, shear force is induced in the longitudinal joint due to leveling forces. These forces might be resisted by weld plates until the grout is placed and cured. In the headed bar joints, a temporary clamp is needed to resist the camber leveling forces until the joints are grouted and sufficiently cured. These shear forces could affect the shear key joints or the interface. In this study, 3D finite element (FE) models were utilized to investigate the effect of the leveling forces of the early age behavior of shear key connections in DBT girder bridges.

Keywords: Accelerated Bridge Construction (ABC), Decked Bulb Tee (DBT) Girder, Differential Camber, Shear Key, Finite Element Model (FEM)

INTRODUCTION

Accelerated bridge construction (ABC) has become more widely popular in recent years. The speed of construction is essential for bridge replacement and repair in order to reduce disruption of traffic and commerce. In ABC, prefabricated bridge elements are usually produced under controlled environmental conditions off site, transported to the construction site, and assembled together using different types of connections. Typically grout material is used to fill these connections. The connection details are typically chosen based on the type of stress that the connection must resist. Sufficient strength and long term performance of the grout material is required and must be equal or better than the components that are being connected. This assures adequate load transfer and long term durability[1]. Decked bulb tee (DBT) girder bridges are considered a promising system for ABC. Adjacent DBT girders are placed side by side and connected together using longitudinal connections. The precast concrete girders along with an integral deck in DBT bridges provide several advantages such as rapid construction, improved structural performance, and enhance durability[2]. The longitudinal connections may consist of weld plates or headed bars and grouted shear keys.

Despite the benefits of these DBT bridges, the differential camber between adjacent girders, especially in a skewed bridge, could cause an issue during construction. The differential camber in DBT bridges should be taken into consideration because there is typically no cast-in-place deck on the top[3]. Several leveling procedures have been implemented to minimize the differential camber between adjacent units, for instance jacking, surcharging, and crane-assisted leveling. However, shear force is induced in the longitudinal joint due to leveling. These forces might be resisted by weld plates until the grout is placed and cured. In the headed bar joints, a temporary clamp is needed to resist the camber leveling forces until the joints are grouted and sufficiently cured.

The shear forces due to leveling of differential camber transferred across the joints for different girder geometries was investigated using a finite element method (FEM) by Oesterle and Elremaily[3]. A magnitude of differential camber equal to 1/8 in. per 10 ft. was assumed. A bridge width of 48 ft was analyzed with different girder depths, different span lengths, and both for skewed and non-skewed bridges. The leveling of an interior girder produced a higher shear force in the joint than leveling an exterior girder. In the FEM, the longitudinal joints were assumed to be rigid with full continuity in the transverse direction. This assumption ignored the effect of the leveling force on the interface between the leveling girder and the longitudinal joints. Thermal load was then applied to the leveling girder to produce a differential camber effect. However, since the leveling girder was attached to the other girders along the edge of the top flange, shear stress was generated between the leveling girder and adjacent girders. The generated shear stress was equivalent to those developed due to leveling procedures. A skew angle caused the shear stress to increase near one end of the longitudinal joint and to reduce near the other end. The maximum shear force in non-skewed bridges was in the range 0.68 kip/ft to 0.87 kip/ft of span length. However, the maximum joint shear force for the 45° skew angle bridge was 1.45 kip/ft. The maximum flexural camber leveling stress was 890 psi and was anticipated to reduce due to creep. The shear force was anticipated to reduce by 35% after three years due to creep. The magnitude of 1.5 k/ft of girder length was suggested as a maximum camber leveling shear force in the design for temporary clamps. The study ignored the effect of leveling camber on the grout and on the interface. Furthermore, the study did not consider the effect of release of the clamp force on the longitudinal joint. If the grout did not gain sufficient strength before removal of the temporary clamp, these shear forces could crack the shear key or girder-key interface. Therefore, a 3D finite element (FE) models were utilized in this research to investigate the effect of the leveling forces on the behavior of shear key connections in a DBT girder bridge.

FINITE ELEMENT MODEL

A 3D FEM analysis was conducted using a commercial software package to investigate the effects of differential camber leveling forces between DBT girders on the behavior of shear key connections. Three DBT girders were modeled and were selected from a bridge constructed on SH 97 over I-90 in Coeur d'Alene, ID. The bridge consisted of two spans with a length of 100.33 ft each with a total width of 43 ft. The bridge utilized six DBT girders with a depth varying from 48.125 in. to 52.875 in. This change in depth was used to adjust the elevation across the bridge's width and span. The bridge utilized a longitudinal joint (shear key) which was grouted with Ultra High Performance Concrete (UHPC) and contained 6 in. spaced non-contact lap spliced reinforcement. Only three DBT girders were selected from span 1 in the (FE) model to reduce the cost of the analysis. The prestressed strand pattern was taken from the bridge drawing. Three dimensional linear elastic brick elements were used to model the girders and the shear keys while 2-node linear 3D truss elements were used to model the strands. The Modulus of Elasticity and Poisson's ratio were assumed for each part as shown in Table 1.

Table 1. Materials Properties

Part	Modulus of Elasticity (MPa)	Poisson′s ratio
DBT	5,988	0.2
Strand	28,500	0.3
UHPC Grout	7,268	0.18

Partitions were created in multiple locations to simplify the geometry and to create a uniform mesh size (Figure 1a). All parts were meshed to 4 in. in the longitudinal direction and a sweep option was used to create a uniform mesh size in the cross section (Figure 1b). Embedded constraint was used to model the interaction between the concrete and the strands. The lap spliced reinforcement of the longitudinal joints was excluded from the model for simplicity. The interaction between the shear keys and DBT girders were modeled using different types of constraints. Tie constraints were assumed between the shear keys and DBT girders. In the tie constraints, two surfaces were tied together during the simulation and the translational and rotational motions as well as all other active degrees of freedom would be equal for both surfaces. The surface of the shear key was modeled as a master surface because it was assumed to be stiffer than the DBT surface, which was taken as the slave surface. The tie constraint was used to investigate the largest magnitude of stress in the shear keys that may have developed due to the release of the leveling force by assuming a perfect bond at the interface. In order to investigate the effects of the release of leveling force on the interface, the interaction between the shear keys and DBT girders were modeled using surface based cohesive behavior. Surface based cohesive behavior assumes that the interface thickness was negligibly small. The traction-separation behavior, which allowed for a de-bonding failure mode, was defined to model the surface based cohesive behavior. The traction-separation model consisted of initially linear elastic behavior followed by the initiation and evolution of damage. The peak contact stresses in normal and in two shear directions (σ_n^o, τ_s^o and τ_t^o) have to be defined in the model. These peak contact stresses occurred when the separation was either purely normal to the interface (δ_n^o) or purely in first or second shear directions (δ_s^o, δ_t^o). The relationship between the traction stress and the effective opening- displacement was defined by elastic stiffness K_{nn}, K_{ss} and K_{tt}. The area under traction displacement curve represented the energy (G_{cr}) needed to create a crack. The model assumed a linear elastic traction-separation prior to damage. The damage initiates when the maximum stress ratio equals unity as shown by Equation (1):

$$Max\left\{\frac{\sigma_n}{\sigma_n^o}, \frac{\tau_s}{\tau_s^o}, \frac{\tau_t}{\tau_t^o}\right\} = 1 \qquad (1)$$

In order to define the cohesive model, σ_n^o, τ_s^o and τ_t^o and K_{nn}, K_{ss} and K_{tt}. had to be defined. These parameters were assumed based on the literature[5]. The study used push off tests to investigate the shear strength capacity between UHPC and concrete using different surface preparations. The results from the deformed surface was used because the failure was at the interface and also the interface of the shear key in the research presented herein was assumed to be an exposed aggregate surface. The study reported the ultimate shear stress along with the elastic and final displacements. The ultimate shear stress, which was corresponding to the elastic slip, was used to calculate the elastic stiffness (K_{ss}). The ultimate shear stress was also considered the peak contact stress for shear (τ_s^o). The energy was calculated as the area under the load-separation curve by assuming bilinear stress-slip relationship. The same stress and stiffness calculated for shear were assumed to be defined as the normal and other shear parameter. The values used in the model are shown in Table 2.

Table 2. Estimate Interface UHPC-Concrete Parameters

Parameter	Value
σ_n^o (ksi)	0.17
τ_s^o (ksi)	0.17
τ_t^o (ksi)	0.17
K_{nn} (ksi/in)	9.44
K_{ss} (ksi/in)	9.44
K_{tt} (ksi/in)	9.44
G_{cr} (ksi-in)	0.0136

Assumed simply supported boundary conditions were defined in the model by constraining the nodes located at the bottom of each end (see Figure 1a). The load was applied at quarter points as shown in Figure 1c.

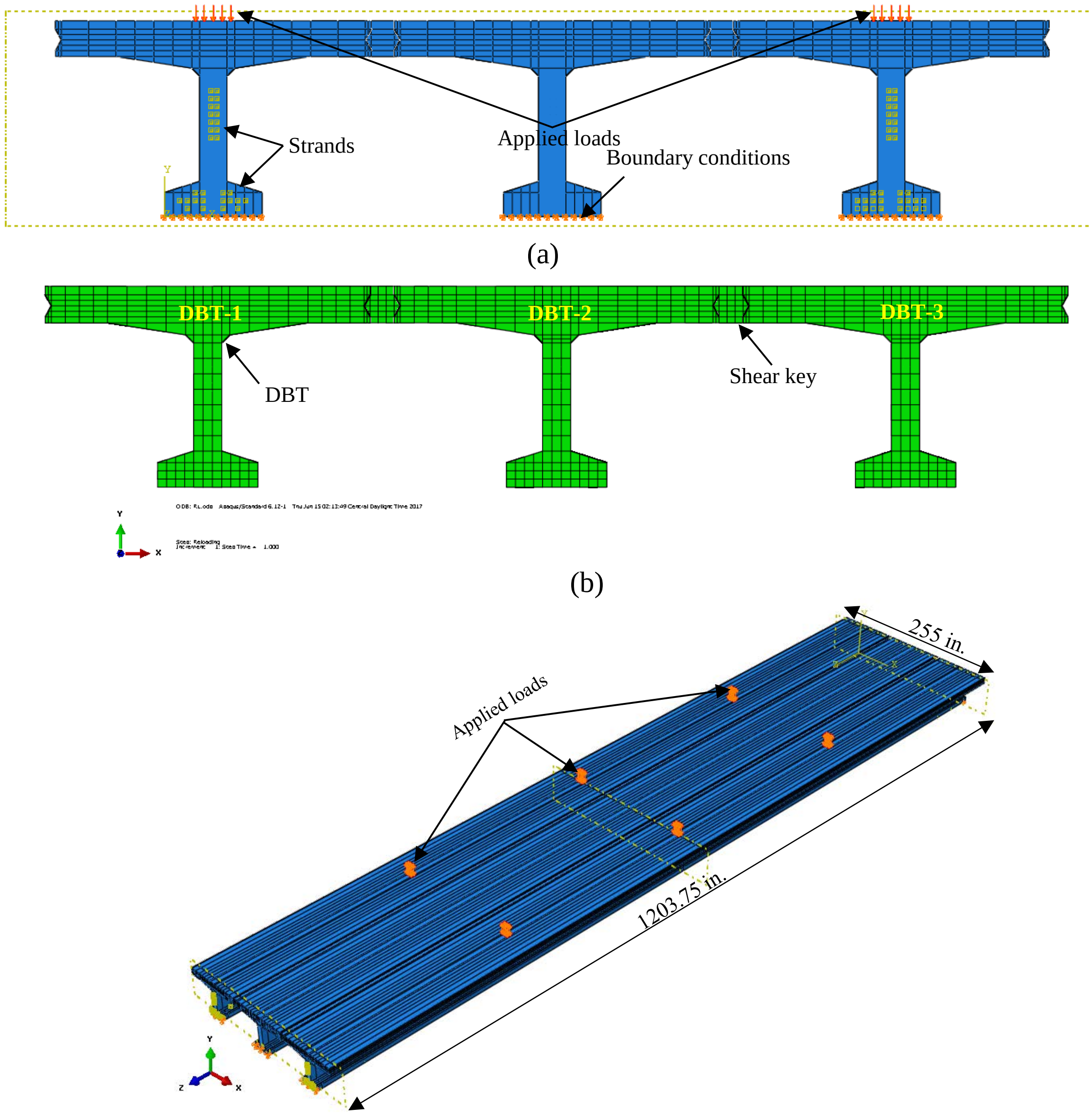
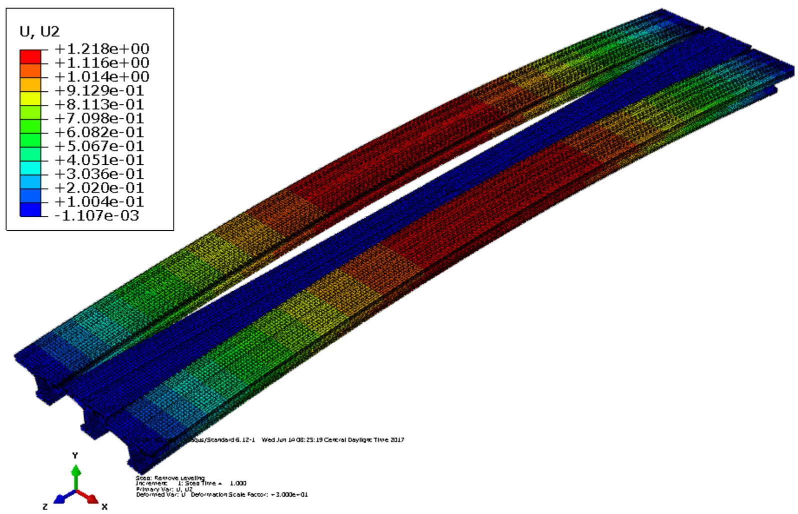


Fig. 1. Finite Element Model: (a) parts' details and boundary conditions, (b) mesh, and (c) loads

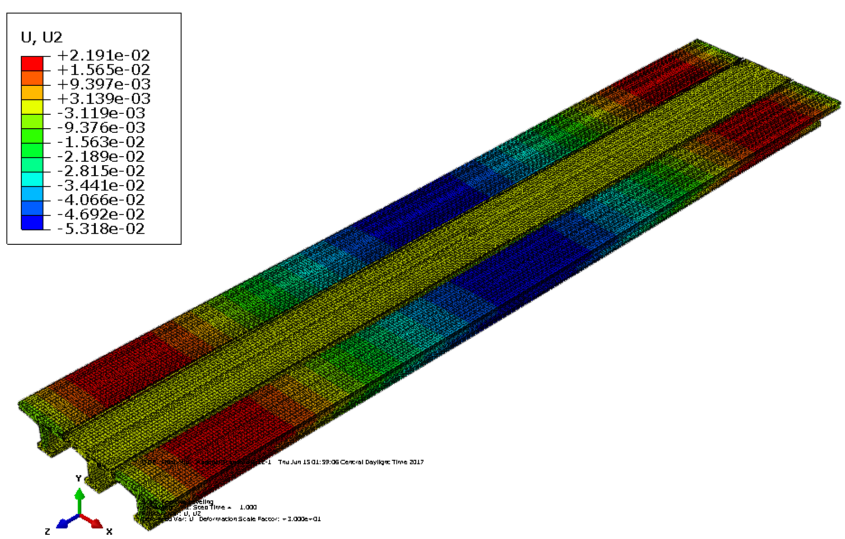
RESULTS

In order to represent the release of the leveling force during the analysis, the (FE) model was run in different steps. In the initial step, all three DBT girders were assumed at the same level and the shear keys were deactivated from the model. In the first step, a prestressing force was applied to DBTs 1 and 3 in order to create a differential camber of 1/8 in. per 10 ft. compared to DBT 2. The value of differential camber was chosen based on the study conducted by Oesterle and Elremaily[3]. The maximum differential camber created between

DBTs 1 and 2 as well as DBTs 2 and 3 at mid span was 1.22 in. as shown in Figure 2a. In the second step, a load was applied to DBTs 1 and 3 in order to re-level the girders and remove the differential camber. Attempts were made to investigate the best location of loading that led to complete removal of the differential camber. When the load was only applied at mid-span, some differential camber was still observed at quarter span. Therefore, the load was applied at both mid and quarter spans to remove the differential camber. However, it was impossible to achieve complete removal as shown in Figure 2b. The load was adjusted to eliminate the differential camber along the longitudinal direction. A magnitude of 25.5 kips was applied at mid-span and 33.5 kips at quarter spans at each load location for DBTs 1 and 3.



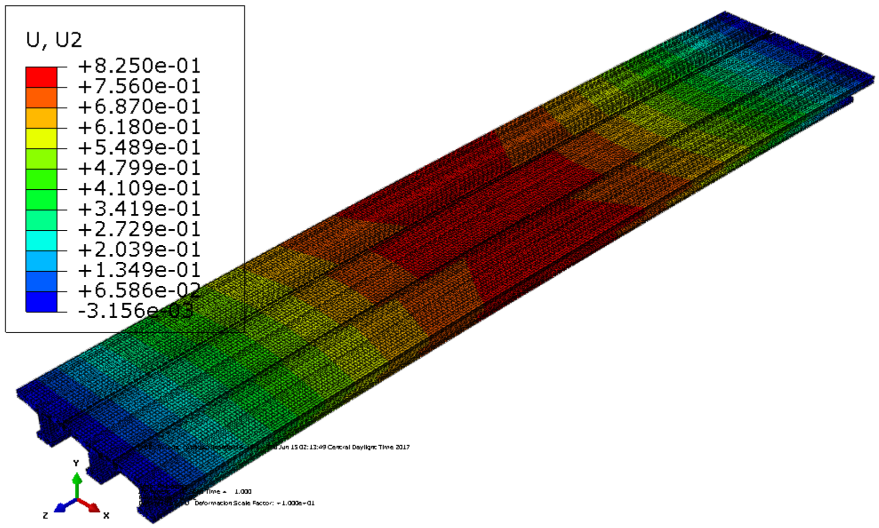
(a)



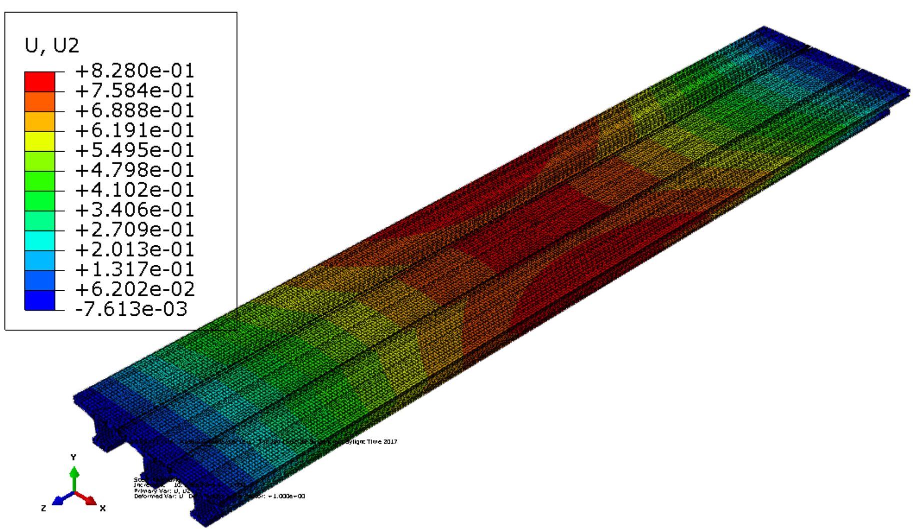
(b)

Fig. 2: Steps of FEM: (a) differential camber, (b) differential camber removal

In the third step, the shear keys were activated in the model for both cases (tie and cohesive constraints) and DBTs 1 and 3 were unloaded in order to represent the case when the temporary clamp was removed as shown in Figure 3a and b.



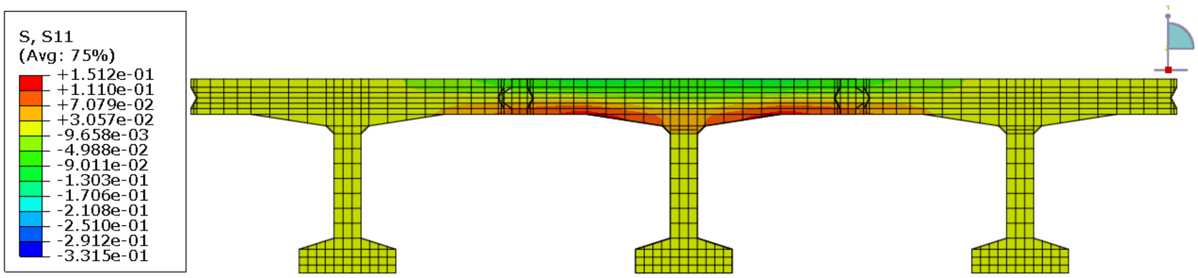
(a)



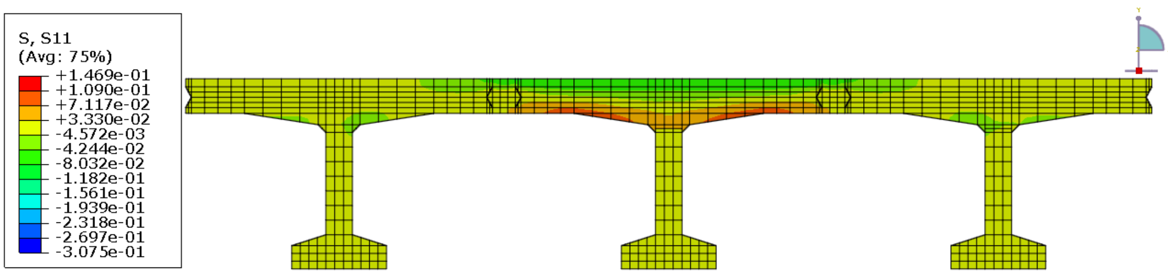
(b)

Fig. 3: Steps of FEM for differential camber at temporary clamp removal (a) tie constraint, (b) cohesive constraint

For both types of constraints (tie and cohesive), the mid-span deflection was reduced in the final step. This indicates the functionality of the shear keys to transfer the load to the unloaded girder. The transverse behavior of the DBT's along with the behavior of shear keys for both types of constraints are shown in Figure 4. The transverse tensile stress was approximately the same for both type of constraints and it was located at the bottom of DBT 2. When DBT 1 and 3 tried to move after temporary clamp force removal, DBT 2 tried to resist this movement which created high transverse tensile stress at the bottom surface of the top flange.



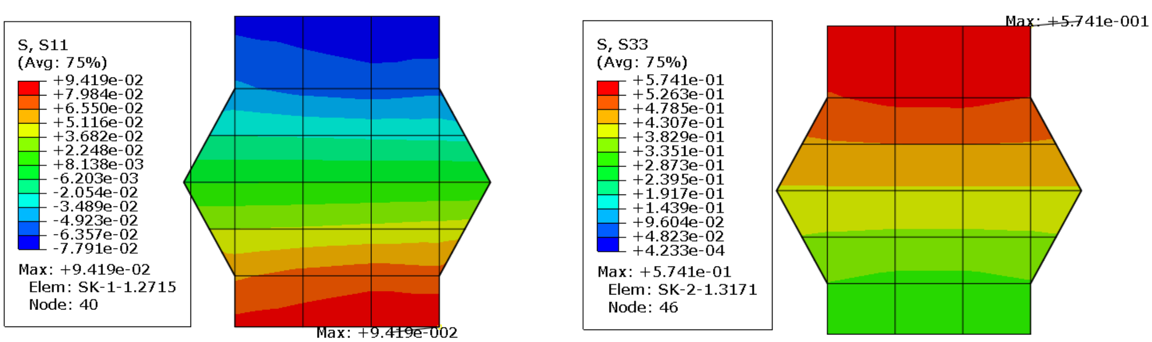
(a)



(b)

Fig. 4. Transverse behavior of DBT's at mid span: (a) tie constraint, (b) cohesive constraint

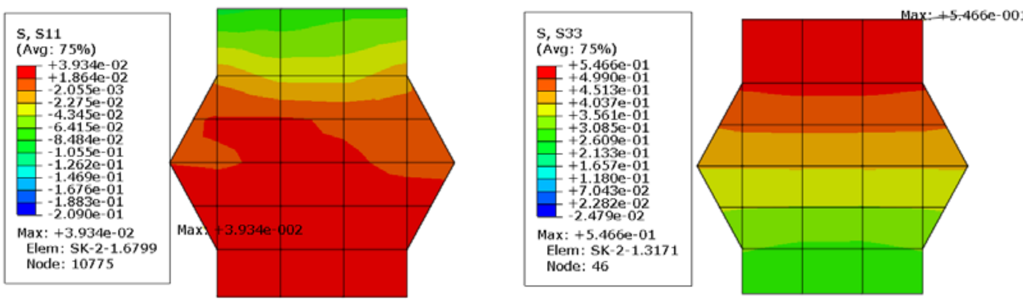
The magnitude of stress in shear keys was also investigated for the tie as well as the cohesive constraints. The transverse and longitudinal tensile stresses in the shear keys for the tie constraint are shown in Figure 5. The shear keys exhibited high stress in the longitudinal direction and almost as the same as the maximum principal tensile stress compared with the transverse direction. This is due to the bending moment that developed from the unloading. The maximum longitudinal tensile stress in the shear keys was about 0.57 ksi at mid-span.



(a) (b)

Fig. 5: Stresses in shear keys under tie constraint: (a) transverse, (b) longitudinal

The transverse and longitudinal tensile stresses in the shear keys using cohesive constraint are shown in Figure 6. The shear keys exhibited high stress in the longitudinal direction compared with the transverse direction. The maximum longitudinal tensile stress was 0.55 ksi at mid span. This magnitude was approximately as the same as the maximum principal tensile stress in the shear keys.



(a) (b)

Fig. 6: Stress in shear keys under cohesive constraint: (a) transverse, (b) longitudinal

The assumed compressive strength of UHPC in this study was 22 ksi at 28 days. The allowable tensile strength of UHPC was calculated using Equation (2) from Russell and Graybeal[5] and was found to be 0.99 ksi.

$$f_{ct}=6.7\sqrt{f_c'} \tag{2}$$

Therefore, the cracks were not anticipated in the shear keys. However, the tensile strength of UHPC at the time of temporary clamp removal must be considered. Furthermore, the early age compressive strength depends on the type of UHPC. The UHPC should have a tensile strength greater than the tensile stress of 0.57 ksi to prevent the cracks for the case investigated.

The effect of the leveling forces on the interface bond strength between DBT girders and shear keys were also evaluated based on the results from cohesive behavior. The damage that was initiated at the interface was evaluated using Equation 1 and is shown in Figure 7. The normal stress was found to be the controlling component in Equation 1. The magnitude of tensile stress due to removing of the temporary clamp was 36 psi. Therefore, the minimum interface bond strength at the time of temporary clamp removal must be garter than 36 psi. This tensile stress may be reduced if the diaphragms are installed before the removing of the temporary clamp. The magnitude of damage initiated was approximately 0.22. This indicates that the leveling force has used approximately 22% of the interfacial bond strength leaving the remaining 78% to deal with other loads.

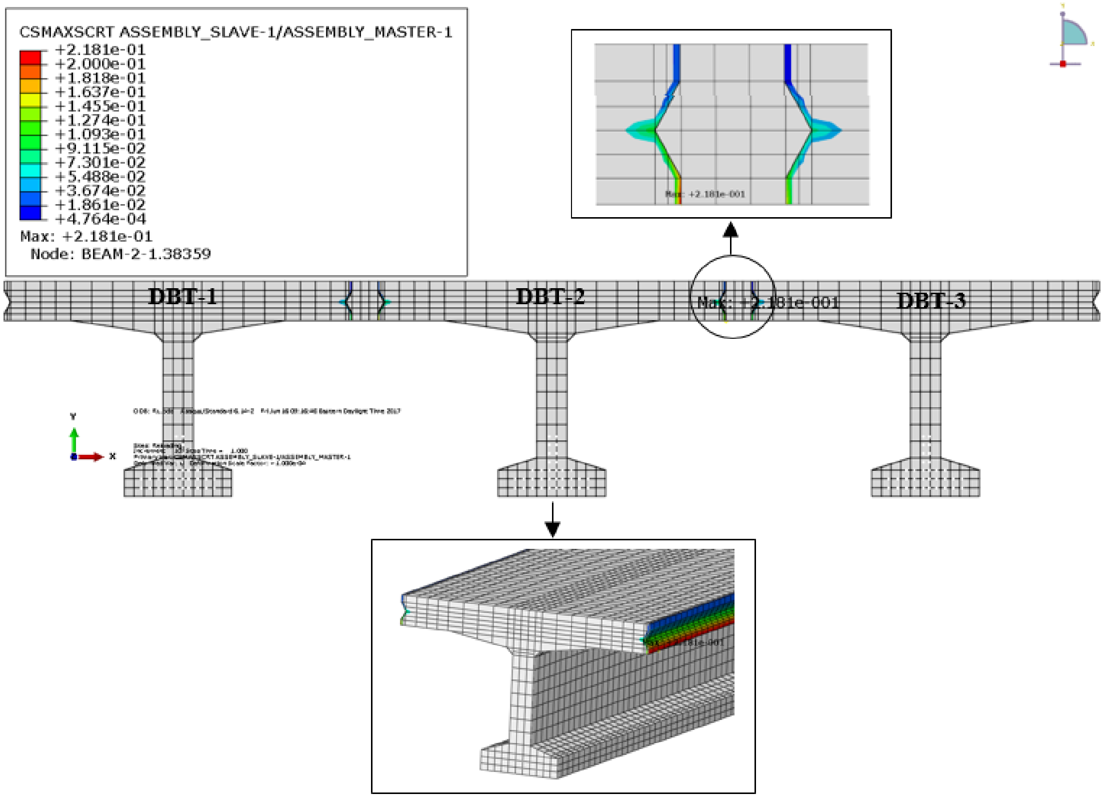


Fig. 7. Interface bond based on cohesive interaction

CONCLUSIONS AND RECOMENDATIONS

A 3D FEM analysis was conducted for an actual bridge to invistigate the effects of the forces used to adjust differential camber in DBT girder bridges. The following conclusions are drawn based on the FEM results:

- It was impossible to completely remove all the differential camber between adjacent DBT girders by using the leveling clamp forces at descrete locations.
- The maxmium longitudinal tensile stress, which was approximately as the same as the maximim principal tensile stress due to the release of the clamp force was in the longitudinal shear key direction. This stress should be less than the tensile strength of UHPC in order to avoid the cracks in the shear key. Therfore, UHPC should have a tensile strength greater than the tensile stress of 0.57 ksi to prevent cracks.
- The release of the clamp force had a significant effect on the interface bond strength between the precast concrete and grout material. Therfore, a high bond should be developed before releasing the clamp force. The minimum interface bond strength at the time of temporary clamp removal must be garter than 36 psi in order to prevent

interface bond failure. However, the bond strength depends on surface preparations at the interface.

- More invistigations are still needed to study the effects of span length, bridge width, skew, girder geometry and shear key connection details on the stress in UHPC shear keys as well as girder-key interface.

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