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Time-dependent Composite Effect of the Curved Steel-concrete Composite Beams in Construction Stage

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Abstract

In order to accurately analyze the mechanical behavior of the steel-concrete composite beams in construction stage, firstly the change law of the shear strength of the stud connectors with the concrete age was studied using the push-out test, in which the time-dependent shear strength formula of the stud connectors was obtained. Secondly, model tests of two simply-supported curved composite beams were carried out during the casting process of concrete slab, the ANSYS finite element models were build with the time-dependent shear strength formula applied in it, and then the experimental and numerical results were verified for each other. On the above basis, a three-span curved continuous composite beam bridge was taken as the sample, by which the influence of the stud connector's time-dependent shear connector strength on the stress behaviors of composite beam in construction stage was studied. The analysis results indicate that the shear strength and stiffness of stud connectors cannot be ignored even when the concrete is in rather early stage, and the early shear strength increases more quickly, whereas the later shear strength slowly. During the segmental casting process of concrete slab, if the casting time interval is between 6 hours and 7 days, the time-dependent characteristics of the early composite action should be considered in the stress behaviors analysis of composite beam in construction stage. Meanwhile, for the hardened concrete segment, the relative slip between the steel girder and concrete slab should also be considered, or else unsafe calculation results will be induced.

Keywords: Composite Beam; Construction Stage; Shear Connector; Time-Dependent; Shear Strength; Early Composite Action

Introduction

During the construction of the steel-concrete composite bridges without supports, usually the concrete slabs are cast in segments. Because the strength of the concrete will increase with the concrete age, as well as the shear strength at the joint surface between the concrete slab and steel girder, as a result, different degree of the time-dependent composite action at the interface will be produced between the adjacent segments which are cast at different time, consequently the structural stiffness of the composite beams will change with different casting sequence and casting time, which will lead to different mechanical characteristics of the composite beams in construction stage.

Generally, the mechanical behaviors of the composite beams are influenced by the type of the transverse connection system, concrete air shrinkage, concrete casting sequence, tension sequence of prestress, and the early composite action between the concrete slab and steel girder.

In order to increase the torsional stiffness of the box composite beam in construction stage, usually horizontal truss and transverse bracing are installed between the flanges and the webs, respectively (Figure 1a). In the analysis hereinafter, the horizontal truss can be simulated into a virtual steel plate with equivalent thickness, thus the steel girder with open cross section become a type of "Quasi-close box section". Fan and Helwig conducted detailed analysis to the mechanical behaviors of the horizontal truss between the upper flanges and the transverse braces between the webs in construction stage, which provides fundamental basis for the subsequent researches [1]. By the finite element method, Kim and Yoo proposed the calculation method of the internal force for the K-type transverse brace inside the steel box beam [2]. Kyungsik and Chai studied the bending behaviors of the box beam with trapezoid quasi-close section and X-type internal transverse brace [3].

In 1975, Long and Csagoly studied the air shrinkage stress of the concrete in the composite beam [4]. Later, researches on the influences of the casting sequence of concrete, slab crack and tension sequence of presetress on the mechanical behaviors of composite beams are carried out [5]. Bradford studied the nonlinear and buckling behaviors of the composite beams without supports in early construction stage [6]. Chavel and Earls analyzed the mechanical behaviors of the curved composite beam with I-shaped section in every loading phase by nonlinear finite element analysis [7]. Nevertheless, the composite action between the concrete slab and steel girder at early concrete ages is not involved in the references aforementioned, and the experimental results from model tests of composite beam in construction stage are still rather rare.

Topkaya et al. analyzed the mechanical behaviors of the curved box composite beams in construction stage, in which the composite action between the concrete slab and steel girder at early concrete ages is considered, and transverse connection system shown in Figure 1a is adopted in the composite beam involved [8,9]. In China, diaphragms instead of transverse trusses are usually used between the webs of steel box composite beam (Figure 1b), while the mechanical behaviors in construction stage are different, on which Zhang and Li et al. have taken some primary studies [9,10].

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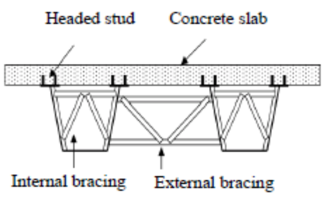


(a) Transverse connection with cross bracing

(b) Transverse connection with diaphragms

Figure 1: Transverse connection of the composite beams.

The change of the composite action with time is reflected by the time-dependent shear strength of the shear connector (e.g. headed stud) which obtained from push-out test. By far, some research results are achieved, such as the shear strength of the shear connectors in the usual steel-concrete and shaped steel plate composite beams, the bearing capacity of the shear connectors under the combined action of axial load and shear force, the stress states of intensive cluster studs, and so on. Nevertheless, the abovementioned researches cannot reflect the change law of the shear connection strength with the concrete age. In 2004, Topkaya et al. carried out the push-out test at 8 concrete ages by self-anchored experimental equipment, in which only the headed stud with the diameter of 19 mm and the concrete with the strength class of S are involved, and the strength parameter at different concrete ages are necessary in the given calculation formula for the time-dependent shear strength of headed stud [11]. Therefore, it is necessary to conduct the push-out tests with different headed stud diameters and concrete matching to provide useful verification and complement for Topkaya's research results, and then propose more practical calculation formula.

Taking curved composite beam with diaphragms as example, firstly the change law for the shear strength of the headed stud connectors with concrete age is experimentally studied by push-out test in this paper. Combined with the parametric analysis by the numerical simulation of ANSYS, the model tests on the mechanical performance of the curved simply-supported composite beams are carried out in construction stage, and the influences of the time-dependent composite action between the concrete slab and steel girder on the mechanical behaviors of composite beams in construction stage is investigated.

Time-dependent shear strength of head stud connectors

Push-out test: Push-out tests for headed stud shear connectors at different concrete ages are carried out. In the tests, the specimens are classified into 7 groups (3 specimens for every group) according to the concrete ages, i.e., 6 h, 12 h, 24 h, 3 d, 7 d, 14 d and 28 d. The concrete slabs on both sides of the headed stud connector are set with the dimensions of 500 mm × 460 mm × 150 mm, and the strength grade of C30, in which the HPB235 rebar with the diameter of 10 mm are configured. The HW250 × 250 profile steel is adopted for steel girder, with the strength grade of Q235, and the height of 510 mm; There are totally 4 headed studs, with the diameter of 16 mm, and the length of 100 mm, are welded on both sides of the steel girder (2 for every side).

The flanges of the steel girder are greased at both sides before concrete casting, which is simultaneously cast and cured with water manually. For the test specimens with the concrete age of 6 h, 12 h and 24 h, they are cast and cured directly below the loading equipment. Loading increment with 3 kN is adopted, when the load-slip curve becomes flat, the loading increment is decreased to 1 kN till the test specimen is fall. Dial indicators are set on the flanges corresponding to the position of headed studs to measure the relative slip between the steel girder and concrete slab.

The dimensions of the push-out specimens and loading equipment are shown in Figure 2.

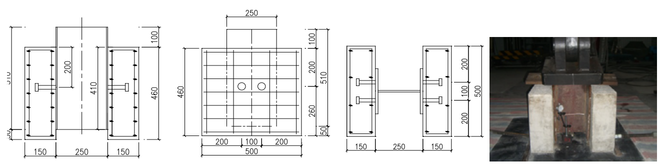
Analysis of the test results: The failure modes of the push-out specimens are divided into two types, i.e., splitting failure of the concrete slab and shear failure of the headed studs (Figure 3).

The main findings of the push-out tests are shown in Table 1, and the load-slip curves with different concrete ages for the specimens in group 2 are illustrated in Figure 4.

Taking the maximum load on the load-slip curves as the ultimate shear strength Q_u, and the slip corresponding to the maximum shear force as the ultimate slip value S_u, the change laws of Q_u and S_u with the concrete ages are then obtained in Figures 5 and 6.

Some findings can be drawn from Table 1 and Figures 4-6, those are

(1) The ultimate shear strength Q_u increases with the increase of the concrete ages, while the ultimate slip S_u shows decreasing trend. For specimens with the concrete age earlier than 3 d, splitting failure mode takes the major position.



(a) Front view (b) Side view (c) Top view (d) Loading equipment

Figure 2: Dimensions of push-out specimens and loading equipment.

(a) Splitting failure of concrete slab (b) Shear failure of headed studs

Figure 3: Failure modes of push-out specimens.

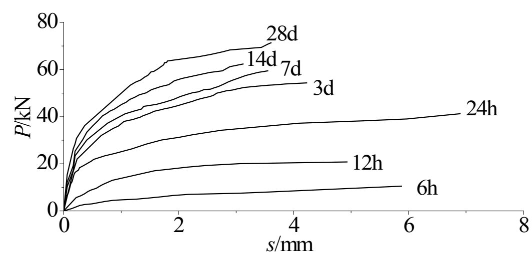


Figure 4: Load-slip curves of push-out specimens.

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(2) Generally, all the load-slip curves indicate the same law, i.e., all the specimens have shown certain early shear strength stiffness, which will increase with the concrete ages, and faster in the earlier stage, gradually slow in the later stage.

Calculation formula for time-dependent ultimate shear strength of the headed stud connectors: Taking the average ultimate shear strength of 3 headed studs in one group with 28 d concrete ages (Q_u^{28}) as the baseline value, some dimensionless data of the ultimate shear strength are obtained from the push-out tests in this paper and Topkaya. By least square method, the fitting curve based on the aforementioned data are obtained in Figure 7, in which the correlation coefficient of the curve is 0.92, and the corresponding calculation formula for time-dependent ultimate shear strength of the headed stud connectors is then shown as follows:

$$Q_u^t = 1.01 Q_u^{28} e^{-\frac{0.56}{t+0.21}} \tag{1}$$

where Q_u^t is the ultimate shear strength of the headed stud connector at any concrete age t, with the unit of day; Q_u^{28} is the measured average ultimate shear strength of the headed stud connector at 28 d concrete age. If there is no any reference test data, the theoretical value can be alterative according to clause 11.3.1 in *Design Code for Steel Structures* of China. For completeness, the fitting curve from by Topkaya is also illustrated in Figure 7.

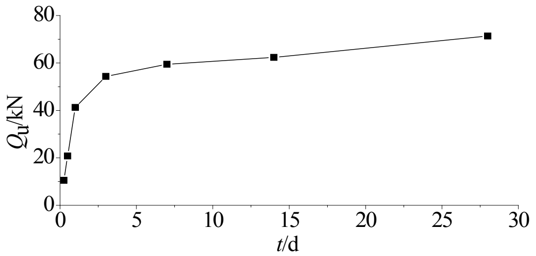

Figure 5: Change law of stud connectors' ultimate shear strength with concrete ages.

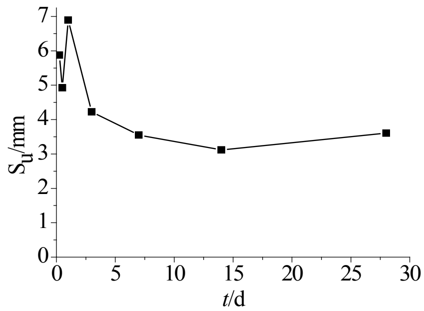

Figure 6: Change law of stud connectors' ultimate slip deformation with concrete ages.

It can be known from Figure 7 that (1) In general, the curve calculated from this paper is close to that from Topkaya. Nevertheless, the calculation formula proposed by this paper can intuitively express the relationship between the ultimate shear strength of the headed stud connector and concrete age *t*.

(2) The ultimate shear strength will not obviously increase after the concrete age *t* exceeded 7 d, and keep broadly unchanged after 28 day, which is usually deemed as Q_u^{28} for the concrete age later than 28 d.

For the cured concrete with age of 28 d, the corresponding shear-slip law of headed stud can be defined by Eq. (2)

$$Q = Q_u^{28}\left(1 - e^{-\beta s}\right)^{\alpha} \tag{2}$$

where Q is the shear force borne by the headed stud; s is the relative slip at the interface between the steel girder and concrete slab under Q; α and β are the calculation parameters that determined by test, and the values $\alpha = 0.7$ and $\beta = 0.8$ can be adopted if no reference test data.

It can be known from the test results in Figure 4 that the stud connectors at different concrete ages show the similar load-slip law, thus for the stud connectors at any concrete age t, the load-slip relationship formula can be approximately given by that of 28 d, just replacing Q_u^{28} by Q_u^t, that is $Q = Q_u^t\left(1 - e^{-\beta s}\right)^{\alpha}$ (3)

Model tests on the mechanical behaviors of curved composite beam in construction stage

Introduction: Two curved simply-supported steel-concrete composite beams which are constructed without supports are taken as the research object. The two beams named CCB1 and CCB2 have the same sectional parameters, span and materials, Each composite beam has single box section, with a length of curve of 6.2 m, a calculation span of 6 m and a radius of curve of 30 m. For the structural details, there are 5 diaphragms are uniformly installed with the spacing of

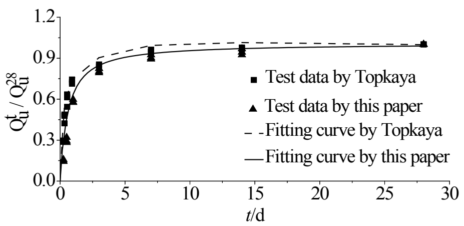

Figure 7: Fitting curve of stud connectors ultimate shear strength.

Concrete age	ultimate slip S_u / mm				Ultimate shear strength of headed stud Q_u/kN			
	Specimen number			Average value	Specimen number			Average value
	1	2	3		1	2	3	
6 h	5.43	5.88	6.21	5.84	9.33	10.5	12.43	10.75
12 h	4.77	4.93	5.33	5.01	18.66	20.78	22.53	20.66
24 h	6.48	6.9	7.23	6.87	32.44	33.8	35.66	33.97
3 d	3.99	4.23	4.44	4.22	52.24	54.34	56.76	54.45
7 d	3.22	3.55	3.77	3.51	57.56	59.45	61.49	59.5
14 d	2.99	3.12	3.33	3.15	60.22	62.33	64.18	62.24
28 d	3.33	3.61	3.7	3.55	69.16	71.34	73.29	71.26

Table 1: Main test results of push-out test.

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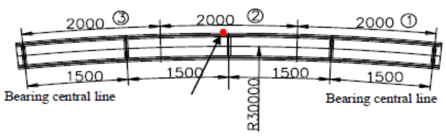
1.5 m and the thickness of 6 mm. For the sectional parameters, the section depth is 270 mm, in which the concrete slab is 70 mm deep and 700 mm wide. The steel girder is fabricated with 235 MPa steel, and the concrete deck utilised C30 concrete, and φ6 mm plain bars are configured for the longitudinal rebar and stirrups. The concrete slab and steel girder are connected by 35 headed studs for one row with the diameter of 13 mm, which are arranged on the flange right above the web, consequently full connection formed.

The concrete slab of CCB1 is cast at one time (so-called instantaneous casting), and the concrete slab of CCB2 uses continuous casting sequence with the segments cast one by one in 3 stages with the time interval of 6 h to study the effect of time-dependent composite action. The sectional parameters and the sequence for continuous casting are shown in Figure 8, in which ①, ② and ③ are the sequence numbers.

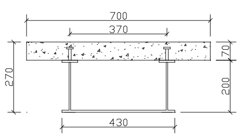
Description of the experiment: Triangular brackets are installed beside both webs to achieve non-supporting construction, on which wooden formworks are laid and then reinforcements assembling are carried out. Two force sensors are set at both bearing to measure the bearing reaction (Figure 9).

The stress status of five sections, i.e., the sections of one bearing, $L/8$, $L/4$, 3 $L/4$ and $L/2$ are measured, where the tangential and radial strain gauges are stuck on the flanges of outcurve. Correspondingly, dial gauges are set at the aforementioned positions to obtain the tangential and radial displacements.

The concrete slab of CCB1 is cast instantaneously, afterwards the strain and dial gauges are read once the casting is completed. For the model beam CCB2, the concrete slab is cast in three stages (Figure 10).



(a) Plane figure of steel girder

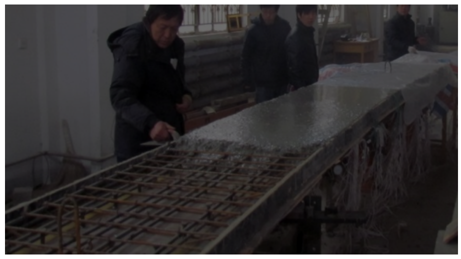


(b) Cross section of composite beam

Figure 8: Dimension of test girder/mm.

Figure 9: Test beams to cast.

(a) The 1st concrete casting of segment.



(b) The 2nd concrete casting segment.

(c) The 3rd concrete casting segment

Figure 10: Segmental casting of the concrete slab of CCB2.

After the first segment is cast, the strain and dial gauges are read immediately. Then the first segment is cured for 6 hours. Before the second segment is cast, all the gauge readings are cleared, and they are read once the casting of the second segment is finished. By the same procedure, the third segment is cast and measured. In the aforementioned casting stages, only the strain and displacement of the current casting procedure are measured, and the final results are superposition of them (Figure 10).

For comparison, both the measured and the numerical results in Chapter 3.3 of the two model beams for the vertical and radial displacement, tangential and radial strain at the flanges of outcurve are shown together in Chapter 3.3.3.

Numerical simulations

The mechanical behaviors of the test beams are analyzed by ANSYS software, and compared with the measured results to verify for each other.

Finite element model: In the FE model of each composite beam, the steel girder is modelled with the shell element SHELL43, the concrete is modelled with the solid element SOLID65. Each headed stud connector between the concrete slab and steel girder is modelled with three

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tangential, radial and vertical COMBIN39 spring elements, to simulate the tangential and radial time-dependent shear-slip relationships, and the vertical time-dependent axial force-lift relationships (Figure 11).

(1) Time-dependent tangential and radial shear-slip relationships

It is assumed that the headed stud connectors follow the same slip law in the tangential and radial directions, so two spring elements are introduced to simulate the tangential and radial shear-slip relationship of the headed stud connectors respectively by connecting the adjacent nodes of the concrete slab and steel girder (Figure 11). According to the test results in Chapter 3.1, firstly the ultimate shear strength of the headed stud connectors at different ages is obtained by Eq (1), which can be introduced in the tangential and radial shear-slip constitutive relationship equations. Secondly, using the above constitutive equations, the real constants of spring elements can be defined by Eq (3), consequently the time-dependent shear behaviors of the connectors can be simulated.

(2) Time-dependent vertical axial force-lift displacement relationship

Considering that the vertical lift deformation between the concrete slab and steel girder is very small after the concrete slab is fully hardened, usually it is ignored in the numerical analysis; however, such lift deformation cannot be ignored when the concrete age is small. Given that there are no relative literatures about the vertical time-dependent axial force-lift relationships of the headed stud connector, hereinafter the relative axial deformation between the concrete and the headed stud buried in it is regarded similar in some ways to that of the bond-slip relationship between the reinforcements and the surrounding concrete; Therefore, the latter is used to approximately simulate the vertical lift deformation, different concrete strength with different ages are introduced into the bond-slip constitutive relationship to consider the time-dependent behaviors, see Eq (4):

$$\tau = (5.3\times10^{2}\delta - 2.52\times10^{4}\delta^{2} + 5.86\times10^{5}\delta^{3} - 5.47\times10^{6}\delta^{4})\sqrt{\frac{f_c^t}{40.7}} \quad (4)$$

where τ is the bond stress with the unit of MPa; δ is the vertical slip of the headed stud relative to the surrounding concrete with the unit of mm; f_c^t is the compressive strength of the concrete at age t, with the unit of MPa, for the ordinary or early cement, it can be defined by Eq (5) according to the code of CEB-FIP:

$$f_c^t = f_c^{28} e^{0.25\left(1-\sqrt{28/t}\right)} \quad (5)$$

where f_c^{28} is the compressive strength of the concrete age of 28 d.

In the finite element model, the axial force borne by the headed stud can be obtained by multiplying the bond force τ by the surface area of the stud body, and the relationship between the axial force and the vertical slip δ can also be defined by the real constants of the vertical spring element.

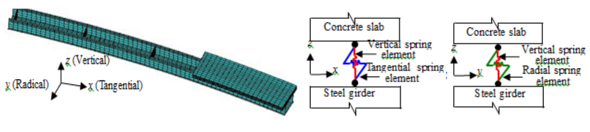
The boundary conditions of the model beam are set as fixed-pinned, i.e., the left bearing is roller support and the right one is fixed. The wet weight of the concrete is simulated by applying surface load at the flanges of the steel girder, which is determined by the equivalent measured load during the concrete casting process. In the post processing, the vertical and radial displacement, tangential and radial strain at the flanges of outcurve can be acquired by defining path in ANSYS. The FE model of CCB2 which uses continuous casting method is shown in Figure 11.

Simulation of the concrete casting: For the beam CCB1, which is cast instantaneously, there is no composite action formed due to the unsolid concrete when the casting process is just completed, so only the steel girder bears all the wet weight, which is simulated by applying surface load on the flanges of the whole steel girder.

With regard to the beam CCB2, which is cast continuously, the headed stud connectors with time-dependent shear stiffness can be simulated by the following steps:

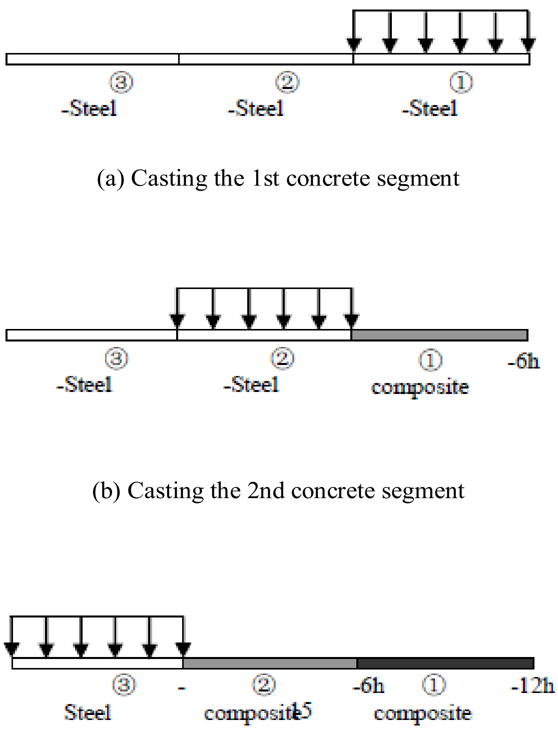
a) When casting the 1st concrete segment, the bearing structures of the 1st, 2nd and 3rd segments are all only the steel girder, in this step only the wet weight of the 1st concrete segment, which is simulated as surface load, is exerted on the corresponding upper flanges (Figure 12a);

b) For the casting of the 2nd concrete segment, while the concrete age of the 1st segment is 6 h, the shear-slip relationship and lift effect of the headed stud connectors can be defined using the constants in the spring element according to Eqs. (1), (3) and (4). At this time, among



(a) The FE model of CCB2 (b) Vertical and tangential spring (c) Vertical and radial spring

Figure 11: Finite element model of CCB2 which uses continuous casting method.



(a) Casting the 1st concrete segment

(b) Casting the 2nd concrete segment

(c) Casting the 3rd concrete segment

Figure 12: Simulation of the concrete casting process.

the bearing structures of the 1st, 2nd and 3rd segments, the 1st segment has turned into the section with the composite action of the concrete age of 6 h, the 2nd and 3rd segments are still only the steel girder. Consequently, the surface load in this step is exerted on the corresponding upper flanges of the 2nd steel girder segment (Figure 12b);

c) For the casting of the 3rd concrete segment, while the concrete age of the 1st segment is 12 h, the 2st segment is 6 h, the shear-slip relationship and lift effect of the headed stud connectors can be defined by the same way aforementioned. At this time, among the bearing structures of the 1st, 2nd and 3rd segments, the 1st segment has turned into the section with the composite action of the concrete age of 12 h, and that of the 2nd segment is 6 h, the 3rd segments is still only the steel girder. Consequently, the surface load in this step is exerted on the corresponding upper flanges of the 3rd steel girder segment (Figure 12c);

d) Superpose the calculation results of the three steps, the final load effect after construction

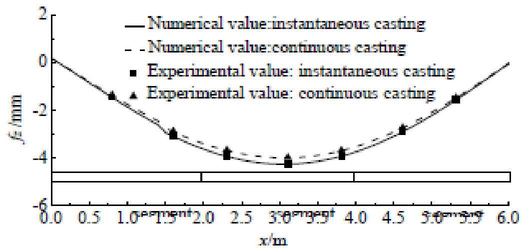
Analysis of calculation results: By the above finite element analysis of the mechanical behaviours of the model beams in construction stage, comparative analysis between the numerical and experimental results of the upper flanges at the outcurve are shown in Figure 13, where the horizontal ordinate x represents the distance to the right bearing, the same hereinafter.

It can be known from Figure 13 that:

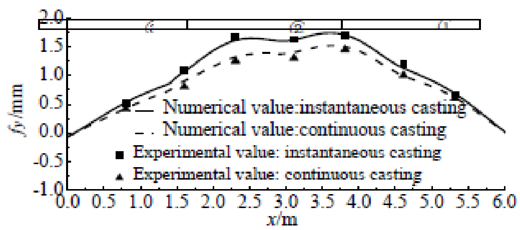
(1) By and large, the calculation values agree well with the experimental results, which indicate that the simulation in the FE model to the time-dependent composite action of the composite beam is reasonable. Because there are totally 5 diaphragms evenly set along the axis of the test beam, which mainly has certain influence on the constrained torsion of the curved beam, therefore some abrupt changes appear at the diaphragm positions (x=0 m, 1.5 m, 3.0 m, 4.5 m and 6 m) in the test and calculation curves for radial stress and displacement. In fact, the existence of diaphragms will inevitably decrease the radial displacement here; meanwhile as some sense of laterally elastic constraint, it will also result in some peaks in the radial stress curve at corresponding positions.

(2) When the concrete is cast continuously, both the stress and displacement in every direction on the upper flanges of outcurve are smaller than that in instantaneous casting, especially for the radial displacement, to be specific the measured radial displacement at midspan reduces by 20%. It is interesting that though casting interval is only 6 h and the concrete still keeps moist, early composite action has appeared at the interface, which makes the stiffness of the composite beam increase.

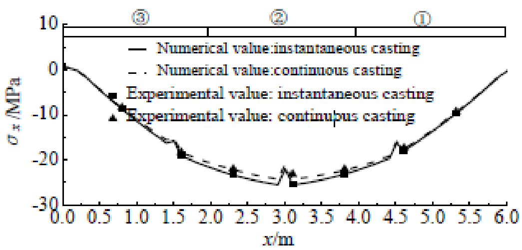
(3) In the continuous casting beam, the stress and displacement along the beam axis are not symmetrically distributed, it is because the concrete segments are cast as the sequence from the 1st to 3rd segment, which leads to unsymmetrical change on the shear stiffness of the interface (the radial displacement is more obvious). In other words, the stress and displacement of the formerly casting segment (the 1st



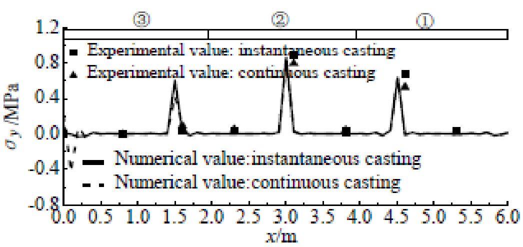
(a) Vertical displacement



(b) Radial displacement

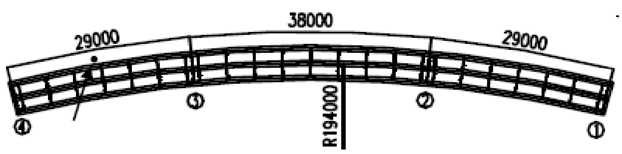


(c) Tangential stress

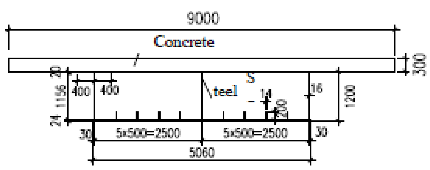


(d) Radial stress

Figure 13: Comparison between the numerical and experimental results.



(a) Plane figure



(b) Cross section

Figure 14: Sectional dimensions of the three-span curved continuous composite beam.

one) are relatively greater, and that of latterly casting segment (the 3rd, symmetric in structure) are relatively smaller, which proves again the existence of the early composite action at the interface of composite beams.

Case studies

Taking a three-span curved composite beam bridge in Beijing South Railway Station as example, the time-dependent composite action between the concrete slab and steel girder of the curved composite beam in construction stage is analyzed by ANSYS software.

Analysis model: The calculation model is a three-span curved continuous composite beam, which has single-box double-cell section, with three calculation spans of 28 m+38 m+ 29 m and a radius of curve R=194 m. Stiffeners are set at the bottom plate and webs, and diaphragms are uniformly installed with the spacing of C=4.5 m and a thickness of 13 mm. The concrete slab is 300 mm deep and 9 m wide, detailed parameters (Figure 14). Q345 qE steel and C40 concrete are used in this bridge. Movable bearings are installed at support 1, 2 and 4, and fixed hinge bearing is installed at support 3.

In the FE model, the steel girder and diaphragms are modelled with plate element SHELL43, the concrete is modelled with SOLID65, and the headed stud connectors are modelled with three tangential, radial and vertical spring elements COMBIN39, (Figure 15), where only part of the concrete slab is shown.

Simulation of concrete casting sequence: There are mainly two types of sequences for the concrete casting process. The first one is cast from one end to another (short for continuous casting), where "①-②-③-④-⑤" is the casting sequence, with the casting interval of 6 h (Figure 16a).

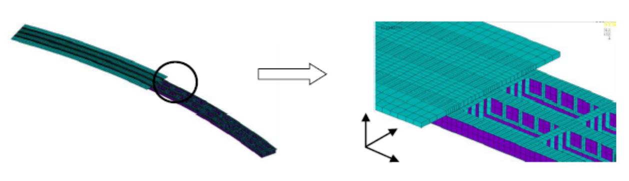
In the analysis by ANSYS, firstly birth-death element technique is employed to kill all the concrete elements, and only the 1st steel girder segment is exerted the wet concrete load by simulating them to uniformly distributed load. Secondly, by the same way, the wet concrete load is exerted on the 2nd steel girder segment, and the concrete elements on the 1st steel girder segment are then activated to form a composite section, with the concrete age of 6 h. By that analogy, there are totally 5 load procedures till the casting works are completed, and the final results after the construction can be obtained by superposing that of every load step. The settings of real constants for spring elements of headed stud connectors and the relationship with the concrete age are the same as that in Chapter 3.3.1.

The second casting sequence is concerned with segmental casting between the sagging and hogging moments areas (short for intervallic casting hereinafter) (Figure 16b), where the 1st, 2nd and 3rd segments are in the sagging moment area, the 4th and 5th in the hogging. The same simulation method as the continuous casting is used in ANSYS.

Analysis of mechanical behaviors: In order to study the composite action at early concrete age, there are four working conditions considered in the analysis:

Working condition I: The composite action at early concrete age is ignored, and the concrete weight is always borne by the steel girder (no composite action);

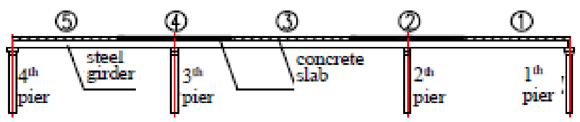
Working condition II: The composite action is considered, without the time-dependent feature involved, as well as the relative slip between the concrete slab and steel girder, whose relevant nodes at adjacent positions are coupled in every direction (no slip);



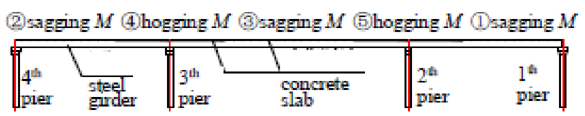
(a) Whole model

(b) Partial enlargement

Figure 15: Finite element model of the three-span curved continuous composite beam.

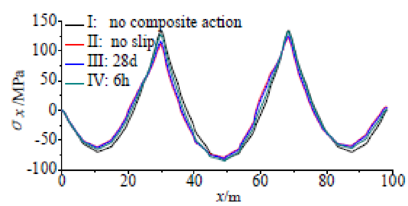


(a) Continuous casting

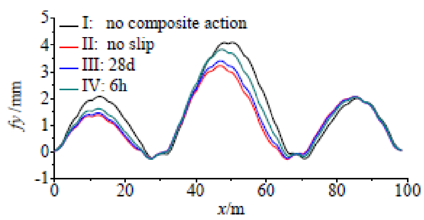


(b) Intervallic casting

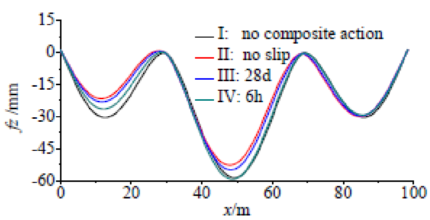
Figure 16: Schematic diagram of concrete cast sequence.



(a) Tangential stress



(b) Radial displacement



(c) Vertical displacement

Figure 17: Stress and deformation on Path 1 when concrete cast from one end to the other end.

Citation: Li Y, Zhang Y, Zhang D, Hou Z (2016) Time-dependent Composite Effect of the Curved Steel-concrete Composite Beams in Construction Stage. J Steel Struct Constr 2: 107. doi:10.4172/2472-0437.1000107

Working condition III: Both the composite action and relative slip between the concrete slab and steel girder are considered, without the time-dependent feature involved. For the cast beam segment, the shear strength of the connectors is calculated with the parameter of 28 d concrete age;

Working condition IV: Both the time-dependent composite action and relative slip between the concrete slab and steel girder are considered, with the casting interval of every concrete segment 6 h.

Continuous casting: The stress and displacement of intersection point at upper flange and web of the outcurve steel girder (the path passing point A along the longitudinal direction is called Path 1 hereinafter) are taken as the analysis object (Figure 14a). It can be known from Figure 13c that the radial stress concentration occurs at the position of diaphragm, not easy to be analyzed, therefore only the tangential stress, radial and vertical displacements are involved in the following analysis. For continuous casting, the aforementioned values along Path 1 are shown in Figure 17, where the horizontal ordinate *x* represents the distance to the right bearing, the same hereinafter.

Figure 17 indicates that

(1) Compared with the working condition I (no composite action), both the stresses and displacements of other working conditions that considering the early-age composite action will decrease;

(2) Compared with the working condition II (no slip), the calculation results of the working condition III (both 28 d composite action and slip are considered) are smaller, which indicates that the interface slip will lead to the decreasing of the global stiffness of the composite beams;

(3) Compared with the working condition III with no time-dependent feature considered, the stress and displacement of the working condition IV with 6 h casting time interval become greater, which indicates that the composite action of the interface will increase with the concrete age;

(4) For the continuous casting, the global stiffness of the structure will continuously grow with the concrete casting from the right end to the left end. Consequently, the final stress and displacement of the composite beam show asymmetrical distribution along the beam axis, which is greater on the right hand side than that on the left.

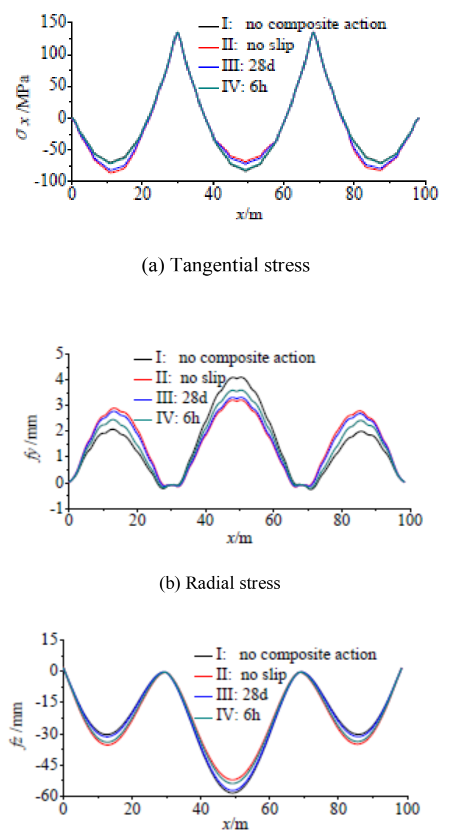
Intervallic casting

For intervallic casting, the aforementioned values along Path 1 are shown in Figure 18.

Figure 18 indicates that

(1) Compared with working condition I, both the stresses and displacements of other working conditions show downtrend. Nevertheless, because of longer midspan, some phenomenon turns out that the side spans grow inversely, but other change laws keep the same with that of continuous casting.

(2) Different from the continuous casting, for the intervallic casting, the structural stiffness increase symmetrically, with a result of approximately symmetrical distribution of the stress and displacement along the axis.

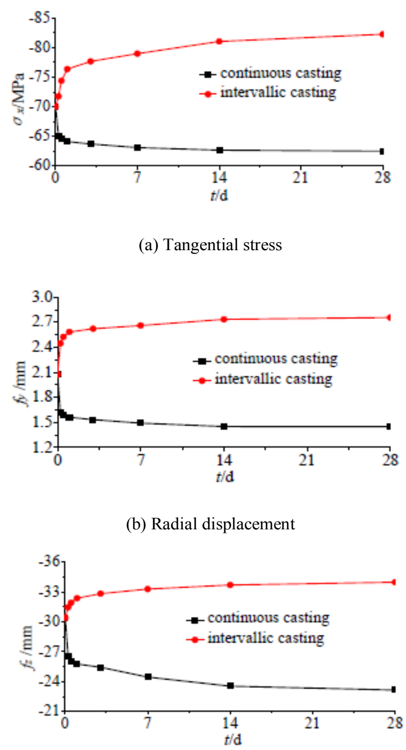


(a) Tangential stress

(b) Radial stress

(c) Vertical displacement

Figure 18: Stress and deformation on Path 1 for the intervallic casting.



(a) Tangential stress

(b) Radial displacement

(c) Vertical displacement

Figure 19: The relationships with concrete ages.

Working condition	Casting time internval	Tangential stress				Radial displacement				Vertical displacement			
		Value/mm	I/%	II/%	III/%	Value /mm	I/%	II/%	III/%	Value/mm	I/%	II/%	III/%
1	No composite action	70.02	/	13.9	12	2.08	/	50.7	43.4	30.41	/	41.4	31.4
2	No slip	61.48	-12.2	/	-1.6	1.38	-33.7	/	-4.8	21.5	-29.3	/	-7.1
3	28 d	62.5	-10.7	1.7	/	1.45	-30.3	5.1	/	23.14	-23.9	7.6	/
4	6 h	65.08	**-7.1**	5.9	4.1	1.62	**-22.1**	17.4	11.7	26.51	**-12.8**	23.3	14.6
5	12 h	64.52	-7.9	4.9	3.2	1.59	-23.6	15.2	9.7	26.09	-14.2	21.3	12.7
6	1 d	64.12	-8.4	4.3	**2.6**	1.56	-25	13	**7.6**	25.76	-15.3	19.8	**11.3**
7	3 d	63.71	-9	3.6	1.9	1.53	-26.4	10.9	5.5	25.43	-16.4	18.3	9.9
8	7 d	63.1	-9.9	**2.6**	1	1.49	-28.4	**8**	2.8	24.45	-19.6	**13.7**	5.7
9	14 d	62.67	-10.5	1.9	0.3	1.45	-30.3	5.1	0	23.54	-22.6	9.5	1.7

Table 2: Comparison of the maximum stress and displacement among different load conditions (continuous casting).

Working condition	Casting time interval	Tangential stress				Radial displacement				Vertical displacement			
		Value/MPa	I/%	II/%	III/%	Value/mm	I/%	II/%	III/%	Value /mm	I/%	II/%	III/%
1	No composite action	70.02	0	-18.8	-14.9	2.08	0	-27.7	-24.7	30.41	0	-14	-10.5
2	No slip	86.19	23.1	0	4.8	2.87	38.4	0	4.2	35.36	16.3	0	4.1
3	28 d	82.26	17.5	-4.6	0	2.76	32.8	-4	0	33.98	11.8	-3.9	0
4	6 h	71.77	**2.5**	-16.7	-12.7	2.45	**17.9**	-14.8	-11.2	31.45	**3.5**	-11	-7.4
5	12 h	74.39	6.2	-13.7	-9.6	2.52	21.6	-12.1	-8.4	31.91	5	-9.7	-6.1
6	1 d	76.36	9	-11.4	**-7.2**	2.58	24.4	-10.1	**-6.3**	32.37	6.5	-8.4	**-4.7**
7	3 d	77.67	10.9	-9.9	-5.6	2.62	26.2	-8.7	-4.9	32.83	8	-7.1	-3.4
8	7 d	78.98	12.8	**-8.4**	-4	2.66	28.1	**-7.4**	-3.5	33.29	9.5	**-5.8**	-2
9	14 d	81.03	15.7	-6	-1.5	2.73	31.7	-4.8	-0.8	33.7	10.8	-4.7	-0.8

Table 3: Comparison of the maximum stress and deformation among different load conditions (Segmental casting).

Influence of the shear connector strength on the mechanical behaviours

In order to perform a further analysis of the influence of different casting time interval on the mechanical behaviors of the curved composite beam in construction stage, besides the casting time interval of 6 h, that of 12 h, 1 d, 3 d, 7 d and 14 d are also calculated. In the analysis, the maximum stress or displacement along Path 1 in the middle of the left span with different casting time interval are taken out, and the relationships with the concrete ages are shown in Figure 19 and Table 2 and 3.

Note: In Table 2 and 3, the values of stress and displacement are absolute ones;

Item I is the comparison between the working condition I (no composite action) and other ones; Item II is the comparison between the working condition II (no relative slip) and other ones; Item III is the comparison between the working condition III (28 d with relative slip) and other ones. Where symbol "+" represents increasing, and "-" decreasing.

Some conclusions can be drawn as follows:

(1) In the early stage of concrete casting, the surface of concrete still keeps moist. It is generally accepted that all the construction loads are borne by steel girder and usually no composite action is taken into consideration. In the case study, with regard to the working condition IV of 6 h casting interval, when the casting of the 5th segment is just finished, the age of the former four concrete segments are 24 h, 18 h, 12 h and 6 h, respectively. The corresponding calculation results of the stress and displacement are just that of working condition I if no composite action is considered. Nevertheless, the calculation results show that compared with working condition I with no composite action, there are 7.1%, 12.8% and 22.1% decreasing in the radial stress, vertical and radial displacements for the working condition IV for continuous casting. For the case of intervallic casting, there are no obvious changes in tangential stress and vertical displacement, but 17.9% increase in radial displacement. In other words, the early composite action cannot be neglected.

(2) After 3 d's curing, the concrete is hardened and certain strength has produced, which is generally recognized that composite action has been formed in the cast segments. In the case study, for the working condition with 1 d casting time interval, when the casting of the 5th segment is just finished, the age of the former four concrete segments are 4 d, 3 d, 2 d and 1 d, respectively. It can be thought that the shear connectors in the segments have reached their ultimate shear strength if no time-dependent feature is considered, i.e., working condition III. However, in the working condition of 1 d with the time-dependent shear strength involved, the calculation results show that compared with working condition III of 28 d, there are 7.6% and 11.3% increasing in the radial and vertical displacements for continuous casting, and there is 7.2% decreasing in tangential stress for intervallic casting. In other words, one can draw conclusions that the early time-dependent effect of the interface in the casting process of the composite beams should be considered.

(3) In order to simplified the analysis, usually the relative slip between the concrete and steel girder is not considered in conventional engineering calculation for composite beams, but the calculation results show that such simplification will result in significant errors on the stress and displacement of steel girder in concrete casting process. To be specific, compared the calculation results of 7 d with that of working condition II (no slip considered, when the casting of the fifth segment is just finished, the age of the former four concrete segments are 28 d, 21 d, 14 d and 7 d, respectively.), there is 13.7% increasing in the radical displacement for continuous casting and 8.4% decreasing in

tangential stress for intervallic casting, which signifies that significant errors of calculation results occur if no relative slip is considered.

Conclusions

(1) The stud connectors have shown certain shear strength and stiffness even when the concrete age is in rather early stage, and the early shear strength increases more quickly, whereas the later slowly, and the increasing speed will be not obvious when the concrete age t exceeds 7 d. The calculation formula for the time-dependent strength of headed stud connectors proposed by this paper introduced into the ANSYS FE model can be well simulated the mechanical behaviours of the curved composite beams when the concrete is cast continuously.

(2) When the concrete slab is cast continuously, the displacements and stresses of the composite beams in every direction are greater than that cast instantaneously, and show asymmetrical distribution along the beam axis, which has made it clear that early composite action has formed at the interface even when the casting time interval is 6 h. The earlier the concrete segment is cast, the greater the composite action and stiffness of the composite beam.

(3) During the casting process of concrete slab, if the casting time interval is between 6 hours and 7 days, the time-dependent characteristics of early composite action should be considered in the stress behaviors analysis of composite beam in construction stage, and the characteristics that the composite action increasing with concrete age should also be considered. When the casting time interval is longer than 7 d among the concrete segments, such increasing effect will not be obvious, and all the casting segments can be calculated with the parameter of 28 d concrete age to consider the composite action.

(4) In the mechanical analysis of the completed steel-concrete composite beam under service load, whether consider the relative slip between the concrete slab and steel girder has little influence on the calculation results, but it should be considered in the cast segments in the casting process, or else unsafe calculation results and engineering potential safety hazard will be induced.

Acknowledgement

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