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研究課題名（和文）Mechanical Behavior of Steel-Concrete Composite Beams Subjected to Combined Hogging Bending and Torsional Moments

研究課題名（英文）Mechanical Behavior of Steel-Concrete Composite Beams Subjected to Combined Hogging Bending and Torsional Moments

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研究成果の概要（和文）：連続合成桁は経済性や支間長が長くとれることによって騒音低減，施工が容易さ，また高次不静定構造であるため耐震性に優れているなどの利点があり広く用いられている．しかし，連続合成桁の中間支点部では負曲げモーメントが作用し，コンクリート床板のひび割れに繋がる可能性がある．合成桁橋の曲線部では，ねじれが生じる．しかし，現在の設計基準ではねじれによる影響を考慮していない．本研究では，ねじれによる連続合成桁への影響を把握することを目的としている．実験と解析結果によりねじれが大きいほど最大荷重が小さくなることが確認できた．また，ねじりと負曲げの相関特性，部分合成を用いた連続合成桁の力学挙動も検討した．

研究成果の概要（英文）：Composite steel and concrete structures have been used extensively in civil engineering structures due to the benefits of reduced noise, easy construction, and improved seismic behavior etc. However, for composite beams in the negative moment regions, concrete slab is usually in tension and easy to crack. For curved composite beams, the composite section needs also to resist the torsional moment. However, there is no design standard considering the effects of torsional moment. This research aims to investigate the mechanical behavior of composite beams under combined negative bending and torsional moments. Based on the results from this study, it has been confirmed that the presence of negative torsional moment will reduce the negative bending moment load carrying capacity of the composite beam. In addition, the interaction relationship between torsion and negative bending moments and the mechanical performance of composite beams with partial shear connections, were also investigated.

研究分野：構造工学・地震工学・維持管理工学

キーワード：Composite Beam　Negative Bending Moment　Torsion　Loading Test　Numerical Analysis

１．研究開始当初の背景

Composite construction of steel and concrete is a popular structural form due to its numerous advantages compared with conventional solutions. The optimal combination of the properties of the two most popular construction materials, i.e. steel and concrete, results in structures that are both safe and economic. Continuous composite beams represent an efficient structural form in many structural systems, such as buildings and bridges, due to additional advantages associated with the favorable redistribution of internal forces across the member and the compliance with of serviceability criteria. However, the design and analysis of continuous composite beams are rather complicated due to their different behavior in positive and negative moment regions. In straight continuous composite beams, negative bending moment regions need special consideration for concrete cracking and steel beam buckling. However, much more serious problems could occur in curved continuous beams, as the combination of the negative bending and torsional moments in internal support regions. Despite the large amount of available experimental data on the flexural behavior of composite beams, experimental data on the behavior of composite beams under combined hogging bending and torsional moments is rather limited. In addition, the current structural design codes do not provide specific rules for the design of composite beams under combined hogging bending and torsional moments; they rather refer to rules established for bare steel sections. Since the behavior of a composite beam differs substantially from that of a plain steel section, the bending moment-torsion moment interaction of composite beams deserves a further investigation. There is increasing demand but with remaining challenges to overcome for design and construction of such structures. As a result, there is a need to undertake a comprehensive study on the mechanical behaviors of composite beams subjected to combined hogging bending and torsional moment.

２．研究の目的

For this research, loading tests will be firstly performed for composite beams with different negative bending/torsion ratios. Based on the experimental observations, numerical models will be built and verified by comparing the numerical data with the experimental results. Thereafter, a parametric study will be performed to investigate the composite beams under different levels of hogging bending and torsional moments. Through this study, (1) the effects of torsion on mechanical behavior of continuous steel-concrete composite beams are investigated; (2) Numerical simulation method for such structures will be proposed and validated by using the test results; (3) interaction between torsion and hogging bending moment will be investigated and the interaction relationship between the ultimate torsion and bending moments will be proposed; (4) effects of shear connection ratios in steel-concrete composite beams will be investigated. Based on the above mentioned research, the general mechanical behavior of composite beams under combined hogging bending and torsional moments will be investigated.

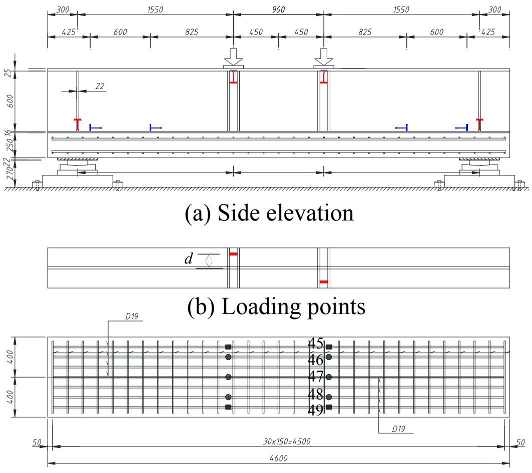


Fig.1 Size dimensions of test specimens (unit: mm)

Fig.2 Loading test set-up

３．研究の方法

This research was conducted through laboratory test and numerical analysis. The research process was divided into four stages: 1) Laboratory test on steel-concrete composite beams under combined hogging bending and torsional moment. Two specimens with different torsion/bending ratios were tested; 2) Numerical simulation of the present laboratory test. A FE model that capable of simulating the present test was developed on the basis of the numerical observations and test results; 3) Parametric study on the mechanical behavior of composite beams under combined hogging bending and torsional moments; and 4) Parametric study on mechanical behavior of composite beams with different shear connection ratios. The general behavior of composite beams under combined torsion and negative bending was investigated.

Two simply supported steel-concrete composite beams were tested in this study, and two eccentric concentrated loads were applied to create the combined torsion and negative bending moments. The specimen was 4600mm in overall length and was simply supported at a span of 4000mm. The concrete slab thickness was 250mm with a width of 800mm. Vertical stiffeners were welded at the supports and loading points to prevent shear buckling failure or crippling of the web before flexural failure. The transverse reinforcement had a nominal diameter of 13 mm and longitudinal reinforcement had a nominal diameter of 19 mm. These bars were arranged on both the top and the bottom of the concrete slab. The longitudinal reinforcement ratio was 2% for all the specimens. Two specimens with same dimensions but different loading conditions. These two specimens are denoted as specimen-1 and specimen-2, respectively. The load eccentricity (d in **Fig.1**) was 10cm for specimen-1 and 15cm for specimen-2. The test set-up is shown in **Fig.2**.

４．研究成果

(1) Load Carrying Capacity and Failure Modes

From the load-displacement curves of the two specimens (**Fig.3**), it can be seen that both specimen-1 and specimen-2 have similar rigidity in the initial loading stage. Two eccentric loads were applied to induce the torsion moments in this study. Due to the limited distance between the two load points, the composite beam between the load points behaves as a “deep beam”, which results in similar deformation between the loaded and un-loaded sides of the section. However, for real structures under a single eccentric load, the rigidity is more likely to become smaller with the increase of the eccentricity of the applied load. Another interesting observation is that the cracking of the concrete slab was little effect on the rigidity of the specimens. This is presumably because of the “deformation compatibility” caused by the two eccentric loads used in this study. In the plastic stage, however, the effects of the torsional moments can be clearly confirmed. The results shown in **Fig.3** indicate that both the yield load and ultimate load of specimen-2 are smaller than those of the specimen-1. Thus, the effect of the torsion moment in reducing the load carrying capacity of composite beams is demonstrated.

All in all, the increase of eccentricity of the loads may result in a decrease of the yield load and ultimate load of the specimens. Due to the loading conditions used in this study, the reduction in rigidity was not confirmed. For real curved continuous steel-concrete beams, the beam rigidity is likely to decrease although further studies would be needed to verify this.

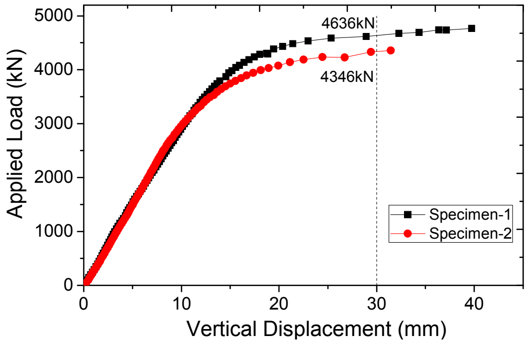
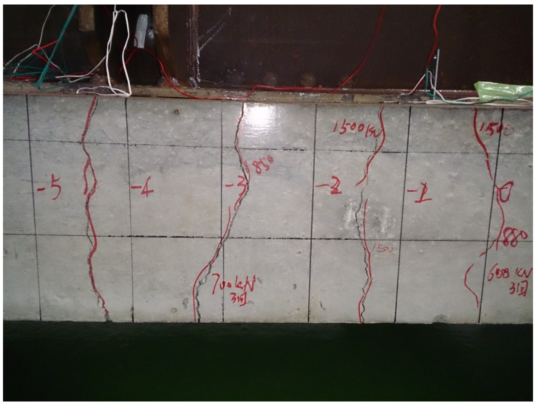


Fig.3 Load and vertical displacement curves[1)]



(a) Crack distribution on the concrete slab

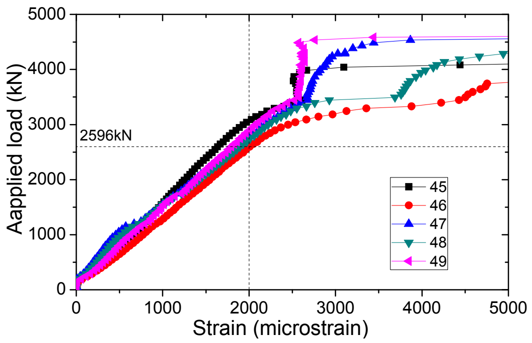
(b) Deformation of the top flange

Fig.4 Failure modes

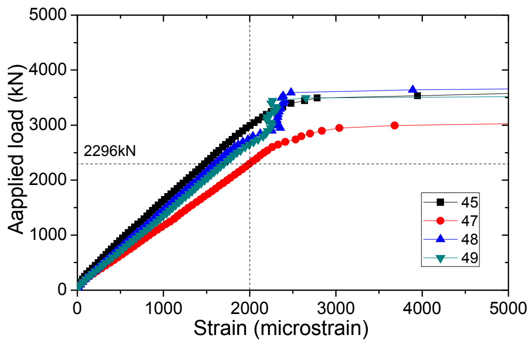
Fig.4 shows the specimen-1 after the loading test. Full depth cracks through the concrete slab and large local deformation of the steel bottom flange were also observed. In spite of this, the rigidity of the beams in the initial loading stages remains stable without obvious reduction, and applied load was still increasing at the ultimate stage. No obvious load reduction or sudden failure was observed in the loading tests.

(2) Strain of the Reinforcement

The strains of the upper layer longitudinal reinforcement on sections near the two loading points were measured. Five strain gauges (No.45~No.49) were attached on reinforcement as shown in **Fig.1**, and the applied load-strain relationships were depicted in **Fig.5**. The results indicate that the strain on the reinforcement increases linearly and slowly before initial cracking of the concrete occurs, and increase suddenly (often referred to as strain jump) when initial cracking occurs. Therefore the composite section has cracks and behaves highly nonlinear even at low load levels. According to the material test, the yield strength of reinforcement is 404MPa. In this study, the yield strain is taken as 2000μ to determine the yield loads of the test specimens. Figure 6 shows that specimen-1 yielded when the load was 2596kN, while the yield load of 2296kN was confirmed in specimen-2. Another interesting phenomenon is that the strain difference between the reinforcement in specimen-1 seems a little smaller than that in specimen-2, which might be due to the difference in load eccentricities. However, this needs further experimental or numerical studies.



(a) Specimen-1



(b) Specimen-2 (gauge-46 was damaged)

Fig.5 Strain development of reinforcement

(3) Load-Slip Relationships

Four LVDTs were employed horizontally to measure the shear slip on the steel-concrete interface. The comparison between specimen-1 and specimen-2 indicates that the longitudinal slips on the steel-concrete interface in specimen-1 are generally smaller than that of specimen-2 in the initial loading stage. As the applied load increases, the slip in specimen-1 approaches and becomes larger than that of specimen-2 at a certain load level. But in general, the applied load and slip relationships in both specimen-1 and specimen-2 are similar to each other. In addition, and the maximum interface slip was found to occur at around the 1/4 span of the composite beam, not at the girder ends. Support conditions and serious cracking of the concrete slab were considered to be the main causes of this behavior. In addition, further numerical analyses should be performed to investigate the effects of the loading and boundary conditions used in this study, and to confirm the real performance of steel-concrete composite beams under combined negative bending and torsional moments.

(4) Elastic Behavior of Composite Beams under Negative Bending Moment

Experimental investigations were carried out on composite girders subjected to negative bending moments applied by two concentrated loads without eccentricities. The test results including load-displacement curve, shear strain and normal strain development in shear studs in different locations were investigated. It was found that the elastic assumptions (no crack on the concrete, and no slip on the interface) can be used for predicating the behavior of the shear connectors in service conditions, particular for the shear strain on shear connections. A comparison between the test results and the theoretical results of shear strain in a stud shear connector is shown in **Fig.6**, in which S3 represents the stud located 1.05m from the end support. In addition, the tensile axial force was also confirmed for shear connectors in typical locations.

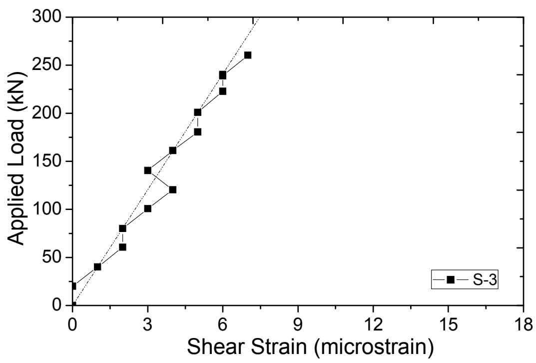


Fig.6 Shear Strain on stud[2)]

(5) Composite Beams under Negative Bending Moment with Partial Shear Connection

The numerical study on the mechanical behavior of composite beams subjected to negative bending moment with partial shear connections was carried out based on nonlinear analyses. Four cases with different total number of shear studs were employed for the parametric study. On the basis of the present results, the following conclusions are made: (1) The comparison between the test and simulation results demonstrate that the numerical model used in this study can reasonably simulate the behavior of the test specimen; (2) The reduction of shear studs within certain limits (25% in this study) can enhance the load carrying capacities of composite beams under negative bending moment, and it will not obviously affect the shear force distribution in both elastic and yield stage. The "cracking relaxation" of composite girders with partial shear connections is considered to be the main reason; (3) If the total number of shear studs beyond a certain limit (25% in this study), the use of partial shear connection will not significantly affect the load carrying capacities of composite beams under negative bending moment[3). However, fatigue design of stud connectors becomes a concern due to significant increase of the shear forces. [1)

(6) Parametric Study on Composite Beams with different Torsion/ Negative Bending Ratios

Parametric study on composite beams with different torsion moment versus negative bending ratios was performed, and the effects of the torsional moment were investigated. The results indicate that the presence of torsion can significant reduced the negative bending moment carrying capacities, which should be considered in design of such beams. The presence of negative bending moment will also reduce the torsional moment carrying capacities, which is different from composite beams under combined positive bending and torsional moments. Further studies on this aspects are needed.

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５．主な発表論文等
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〔産業財産権〕

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〔その他〕
ホームページ等

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