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Stress concentration analysis of an orthotropic sandwich bridge deck under wheel loading

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ABSTRACT

The stress concentration law of a steel plate–polyurethane sandwich bridge deck under wheel loading is studied via experiment and numerical calculations. The results show that the stress concentration of sandwich plates without stiffening ribs is <1/3 that of the corresponding general single-layer steel plate (whose thickness is the same as the total thickness of the two steel faceplates in the sandwich plate) under a local uniform force. The cracks at the partial penetration fillet welded connection between the bridge deck and stiffening rib are in the most unfavorable situation when the wheel acts on the bridge deck just above the longitudinal stiffener. The maximum stress value of the stiffening rib weld of orthotropic sandwich bridge decks with a double-spaced longitudinal stiffener is ~1/3 that of general orthotropic steel bridge decks.

1. Introduction

Many fatigue cracks found in orthotropic bridge decks are caused by high stress concentrations at the longitudinal welds between the stiffening rib and the bridge deck under repeated wheel loading [1–3], seriously affecting traffic safety on bridges [4,5]. To solve this problem, several methods have been explored, including bonding a thin plate of reinforced concrete onto the steel bridge deck [6,7] and bonding a second steel plate to the existing steel bridge deck by a thin epoxy layer or thick polyurethane core [8–10]. Of special interest is the later solution of using steel–polyurethane sandwich plates, as has initially been used in ship building. Currently, steel–polyurethane sandwich plates have been successfully applied to several bridges [11]. A steel–polyurethane sandwich plate is a sandwich plate in which a polyurethane core layer is filled between two steel faceplates; the core layer may be solid or hollow honeycomb. Polyurethane, whose density is ~1/7 that of steel, has greater elasticity relative to steel. The steel–polyurethane sandwich plate has advantages such as high stiffness, anti-aging characteristics, and high impact resistance, and its use thus greatly reduces the extent of local stress concentration and decreases the number of stiffening ribs needed [12]. Because of these advantages, this kind of sandwich plate deserves further research as well as promotion [13,14]. For orthotropic non-sandwich steel bridge decks, researchers have studied the stress concentration under the action of wheel loading [4,5], but there is still no corresponding report on orthotropic sandwich bridge decks.

To provide references of mechanical properties for the wide application of this type of bridge deck, in this paper we study the effect of wheel loads in different positions, both experimentally and numerically, on the stress concentration for two groups of plate specimens. The first group consists of specimens with a sandwich plate and a single-layer steel plate of the same plane size without stiffening ribs. The second group consists of specimens with an orthotropic sandwich deck and an orthotropic single-layer steel deck of the same plane size deck but with stiffening ribs. All the specimens are simply supported on four edges. Finally, the stress concentration distributions of the specimens in the same group are compared, and the performance of the sandwich bridge decks for reinforcing general bridge decks is demonstrated.

2. Stress concentration for the first group of plate specimens

The loading area of the wheel can be regarded as a local area relative to the bridge deck area, so the wheel load can be regarded as a uniform distribution local force. The wheel load will cause stress concentration on the bridge deck. Since stress concentration is the main cause of the fatigue damage of bridge decks, it is necessary to compare and study the stress concentrations of different plates.

In the first group, a rectangular sandwich plate and a single-layer steel plate (720 mm long and 350 mm wide) are used. The thicknesses of the upper and lower steel faceplates of the sandwich plate are both 2 mm. The thickness of the core of the steel–polyurethane sandwich

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plate is commonly 25 to 50 mm in engineering practice, but the experimental specimen we used is scaled to a quarter of the size of a real structure, and therefore the thickness of the core is 10 mm (general thickness) in the normal range. The material properties of steel plate and polyurethane are listed in Table 1.

The wheel load is simulated as a partial uniformly distributed load $q = P/(60 \times 20)$ (N/mm^2) on the local area of 60 mm × 20 mm, in which P is the jack force. The loading area of the wheel is chosen according to China's bridge design specifications (JTG D60-2004). The plane dimension of the first group of specimens is shown in Fig. 1. To ensure reliable adhesion of the steel plate to the core layer within the scope of the test load, the polyurethane core is produced by a professional manufacturer after sandblasting the interface of the steel panels and positioning the interlayer space and soldering edges (see Fig. 2). The same steel plate material is used for the single-layer steel plate, whose thickness is 4 mm, which is the same as the total thickness of the two steel faceplates in the sandwich panel.

2.1. Experimental test

At the top and bottom of the two-plate specimens, strain gauges were glued to record the strains in orthogonal directions (with strain gauges being positioned densely near the local uniform load). Strain gauge numbers on the bottom of the first group of specimens are shown in Fig. 3. The plates were simply supported on four edges and were loaded using a mechanical jack progressively by 200 N every 5 min. Meanwhile, the points' strains in the orthogonal direction of the plate were recorded (see Fig. 4). In this experiment, the local distributed load was acting on the plate center. Based on the recorded strain values, the maximum stress of the steel plate was less than its yield strength; therefore, the steel was in the elastic range. The strains are then converted into stresses according to the elasticity modulus of the steel plate.

2.2. Numerical calculation

The ANSYS software (large-scale general finite-element analysis software with a broad application) is adopted to calculate the models of the sandwich plate and the single-layer steel plate mentioned above. Their elements are meshed along the longitudinal and transverse directions at 20 mm intervals but smaller intervals are used at the positions of local load and strain collection points. The single-layer steel plate is made of plate elements (shell93). In total, each model has 820 elements and 890 nodes. The sandwich plate, which is simply supported on four edges, is made of sandwich plate elements (shell99). In the shell99 element, the material properties (see Table 1) of the faceplate and the core layer can be defined separately. The adjacent layers share the same nodes. The shell99 elements define these nodes as consolidation points and can be divided into three layers along the plate thickness. The stress output is given at the upper, middle, and lower points of each layer. The boundary condition used in the finite-element model is also simple support on four edges (see Fig. 5).

Table 1
Material properties of the specimens.

Material	Steel plate	Polyurethane
Elastic modulus (MPa)	2.0×10^5	800
Poisson's ratio	0.3	0.46
Yield strength (MPa)	335	–
Gravimetric density (kN/m^3)	78.5	11.5

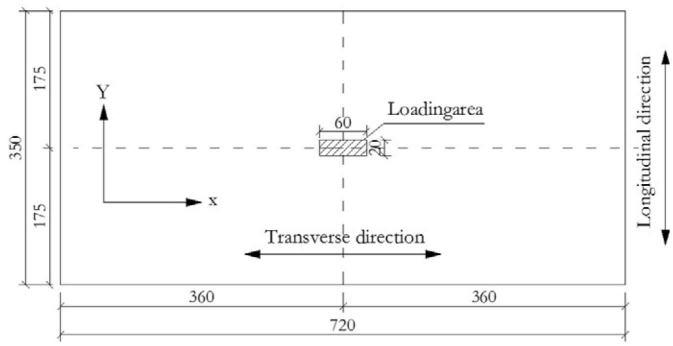

Fig. 1. Dimensions of the first group of specimens (mm).

2.3. Comparison of the stress distributions from experiment and numerical calculation

The strain gauge numbers of strain collection points at the bottom of the sandwich plate and the single-layer steel plate are shown in Fig. 3. The stresses from the experiment and numerical calculation of each collection point are shown in Figs. 6 to 9 for a jack force $P = 2$ kN. These stresses are the bending normal stresses in the two orthogonal directions of the plate.

As seen in Figs. 6 to 9, the experimental results and the finite-element calculation results at each collection point for the two kinds of plate are consistent. Whether the stress σ_x or σ_y of the single-layer steel plate is more than three times that of the sandwich plate. The closer to the center (No. 9) of the local distributed load, the greater the stress difference is. The stress distribution curve for the sandwich plate is flat, but the curve for the single-layer steel plate is steep. This indicates that the former has a lower stress concentration than the latter. For the stress magnitude, although the stress σ_y is typically greater than σ_x and the stress of the sandwich plate is less than that of the single-layer steel plate whose total thickness is the same as that of the two steel faceplates, the above results give a quantitative description of how much smaller it is.

3. Stress concentration for the second group of plate specimens

In the second group, the orthotropic sandwich deck with stiffening ribs simulates the general steel bridge deck, the sandwich plate's length simulates the space between two transverse ribs along the longitudinal direction of the bridge, and the width simulates the width of two cars in the transverse direction of the bridge according to China's bridge design

Fig. 2. Sectional view of the sandwich plate experimental specimen.