# Behavior of glulam beam-orthotropic steel deck hybrid bridge structure

○KISS Lajos*, SASAKI** Takanobu and USUKI Seizo***

* Dr. Eng., Visiting Researcher, Institute of Wood Technology, Akita Pref. University
(11-1 Kaieizaka, Noshiro, Akita 016-0876, Japan)
** Dr. Eng., Assistant Prof., Institute of Wood Technology, Akita Pref. University
(11-1 Kaieizaka, Noshiro, Akita 016-0876, Japan)
***Dr. Eng., Prof., Dept. of Civil and Environmental Engineering, Akita University
(1-1 Tegata, Gakuen-machi, Akita 010-8502, Japan)

**ABSTRACT** This paper presents results of an experimental and analytical study concerning a glulam beam-steel deck hybrid bridge, proposed by the authors. The bridge prototype was designed for a truck load of 250 kN. Test results of a one-third scale hybrid bridge model, having a span of 5.0 m and a width of 2.1 m, subjected to bending and failure test showed that the composite beam theory could closely predict the pre-failure behavior of the tested structure. In addition to this approach, a three-dimensional finite element structural analysis is being performed in order to be able to describe more accurately the behavior of hybrid structure as well as the interaction between structural members. The glulam-steel system comprises an orthotropic steel deck, two double glulam beams with one upper and two lower, vertically inserted glued-in steel ribs. The finite element model consists only of a quarter of the tested model, all members being simulated by solid elements.

***Keywords***: *glulam, orthotropic steel deck, hybrid structure, failure test, finite element*

## 1. INTRODUCTION

Japanese society is a living example that modern and traditional can exist and work at the same time, together. Engineers worldwide and in Japan try to follow this direction and apply this way of thinking in structural design. Building modern timber bridges using glued laminated timber combined with traditional structural materials, such as concrete or steel, is one example. The Bochu Bridge[1], built in Akita Prefecture in 2001 is one of the several steel-timber hybrid bridges built in Japan. In the case of this bridge, the glulam main girders are reinforced with vertically inserted steel ribs at the top and bottom surfaces. An orthotropic steel deck forms a hybrid structure with the girders, being welded to the upper inserted reinforcement. The Bochu Bridge has a length of 55.0 m with two continuous spans, achieved through four joints composed of field welding of the lower inserted steel reinforcements, as well as welding the deck plates. For bridges of this scale, this type of hybrid solution is preferred, because it is easy to design and build.

A comprehensible design method is necessary to make this glulam-steel hybrid bridge structure more available and familiar for clients and bridge designers. The authors proposed the use of plastic composite beam theory as a simple, but reliable way of design for this type of bridge. In order to validate the adaptability of this theory for this type of glulam beam-steel deck hybrid structure, experimental verification was necessary. This reason determined the authors to prepare a reduced scale model of an orthotropic steel deck-glulam beam hybrid bridge for short and medium span bridges, initially using Douglas fir glulam material for the main beams and steel for the ⊥-shaped floor beams[2]. In order to stimulate the use of the widely planted Japanese cedar for structural applications, in a newly designed structure Douglas fir is replaced by Japanese cedar. Here, Japanese cedar is used not only for the main beams, but for the floor beams, too[3]. This paper presents the results of the failure test performed, compared to the ones determined analytically by the plastic composite beam theory[4].

## 2. BRIDGE MODEL

The tested bridge structure consists of an orthotropic steel deck, attached to two double glulam main beams made of Japanese cedar. It is a reduced model (see Fig.1), being one-third the scale of a prototype bridge[5]. Thus, the total length of the orthotropic steel deck plate is reduced to 5.2 m (the span to 5.0 m), its width to 2067 mm and its thickness to $t_d$ = 4.5 mm. The deck plate is stiffened by eight U-shaped longitudinal ribs and seven double glulam floor beams, whose size becomes 60x250 mm each, arranged with an interval of 833 mm. The variation of the width of main beam takes place from $b$ = 60 mm to 93.5 mm at near beam-ends, in order to overcome shear forces developed by reactive forces on the support. This happens on a length of 335 mm, taking a gradient of 1:10, since no other specification exists for it. The length of widened beam portion is 1015 mm (see Fig.2). The depth of main beam is $h$ = 300 mm. The cross section of widened main beam at support, together with an end floor beam is shown on the left side of Fig.1. The right side of the same figure shows the cross section of main beam at midspan and an intermediate floor beam.

The main beams are doubly reinforced by two sets of vertically inserted, glued-in steel ribs, whose size is also reduced. The compression reinforcement is a single rib of a dimension of 3x44 mm. The tension reinforcement consists of two ribs, each having a cross section of 6x70 mm. The inserted steel rib on the compression side serves as shear connector between the deck and the main beams, while the role of the glued-in steel ribs on the tension side of the main beams is to compensate the longitudinal axial strength. Thus, a part of the steel deck (determined by the effective widths $\lambda_1$ = 239 mm and $\lambda_2$ = 577 mm, obtained by applying the Japanese shear lag formula for roadway bridges), the upper and lower ribs and the double glulam main beam form a composite beam. Therefore the plastic composite beam theory can be used to calculate the bending and shear stresses. The composite beam discussed in this paper is defined as the glulam-steel hybrid structure within width $\lambda_1 + c + \lambda_2$ (see Fig.1).

The wood material used for the reduced model was Japanese cedar of strength grade E75-F240 JAS (Japanese Agricultural Standard), while the steel material used for the inserted steel ribs as well for the orthotropic steel deck was SS400. An experimental value of bending moment capacity of Japanese cedar glulam was used for analytical calculations, being equal to $\sigma_{y,W}$ = 39 MPa. The experimental modulus of elasticity of Japanese cedar glulam is $E_W$ = 9 GPa, the shear modulus is $G_W$ = 601 MPa. The experimental yield strength $\sigma_{y,S}$ = 297 MPa and the allowable bending stress $\sigma_{ba}$ = 137 MPa was used for SS400. The modulus of elasticity of steel equals $E_S$ = 206 GPa. The bridge was designed using the plastic composite beam theory, where all steel is converted to an equivalent wood area, resulting in a transformed section[6].

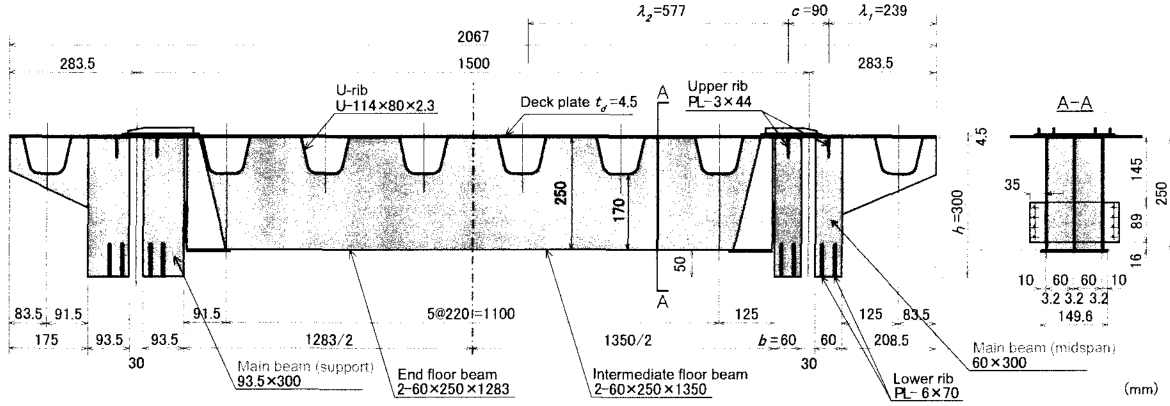


**Fig. 1 Cross section of tested hybrid bridge model**

## 3. FAILURE TEST

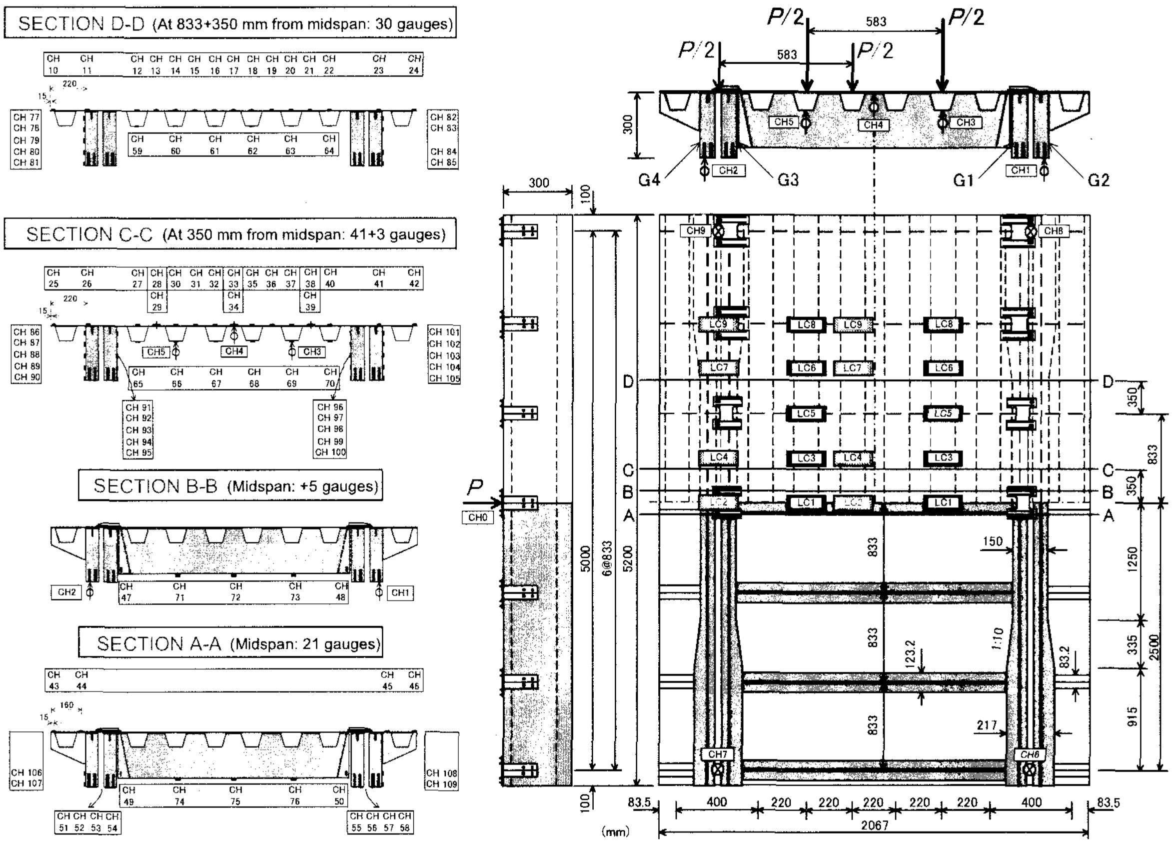


**Fig. 2 Tested bridge model with all load cases, investigated sections and strain gauge positions**

The orthotropic steel deck-glulam beam hybrid bridge model was constructed, instrumented and tested to bending and failure at the structural testing laboratory of the Institute of Wood Technology, Akita Prefectural University, situated in Noshiro City, Japan.

Prior to failure test the model was also subjected to nine bending tests, corresponding to nine loading cases. The difference between these cases (LC1 to LC9, see Fig.2) was the position of the applied truck wheel load. A load-controlled testing machine loaded the simply supported model.

The failure test was performed at loading position LC2. A total number of one hundred strain gauges (see Fig.2) were installed at four different cross sections along the hybrid bridge model. At sections A-A and B-B gauges were installed to the bottom of floor beams, to steel side plates and to lower inserted ribs. At sections C-C and D-D gauges were applied along the depth of double glulam beams, on the upper surface of orthotropic steel deck and the bottom of U-ribs.

Fig.3 shows at loads $P_N$ ($N = Y, P, U$) the deflection of U-ribs measured during failure test at section C-C by deflection meters CH3, CH4 and CH5, as well as deflection of main beams G4 and G2 measured at section B-B by deflection meters CH2 and CH1, respectively. For main beams at section B-B analytical deflection values are also included, closely following the experimental data.

Fig.4 gives a cross section view of the experimental and analytical strain distribution of the deck plate, U-rib, lower ribs, floor beam and side plates (for the position of gauges see Fig.2).

The analytical strain distribution is given for deck plate, U-rib and lower ribs at analytical ultimate load $P_U = 243.7$ kN.

Distributions in Fig.4 are assumed to be uniform and limited by width $\lambda_1 + c + \lambda_2$ (see Fig.1). Local deformation of deck plate near loading caused a non-uniform distribution (section C-C). Except this and the strain of lower ribs in main beams G4 and G3, all other experimental data follow closely the analytical predictions.

Fig.5 shows the longitudinal strain distribution of main beams in a lateral view at analytical ultimate load $P_U = 243.7$ kN.

Due to the separation of lower ribs of main beam G4 as an effect of the increased loading, composite action of glulam-epoxy-steel could not be achieved, resulting in different strain values.

Drawing the analytical $P$-$\delta$ curves determined for CH2 and CH1 by the composite beam theory, we obtain curves that are very comparable to the measured ones (Fig.6).

The experimental value of the ultimate load (failure load), corresponding to the ultimate bending moment is $P_{U,exp} = 266$ kN. This value is about 9% higher than the analytical value of ultimate load $P_U = 243.7$ kN, showing the ability of the composite beam theory to closely predict the structure failure load.

The failure of the model occurred in a ductile manner. Eight distinct failure positions were observed during the test (see failure positions ① to ⑧ in Fig.6), flexural failure starting from a knot situated at the tension side of beam G4.

After failure position ⑦ the load-deflection curve rises again until failure position ⑧ due to the rigidity of the deck. Brittle failure with only one lower rib was observed in earlier tests.

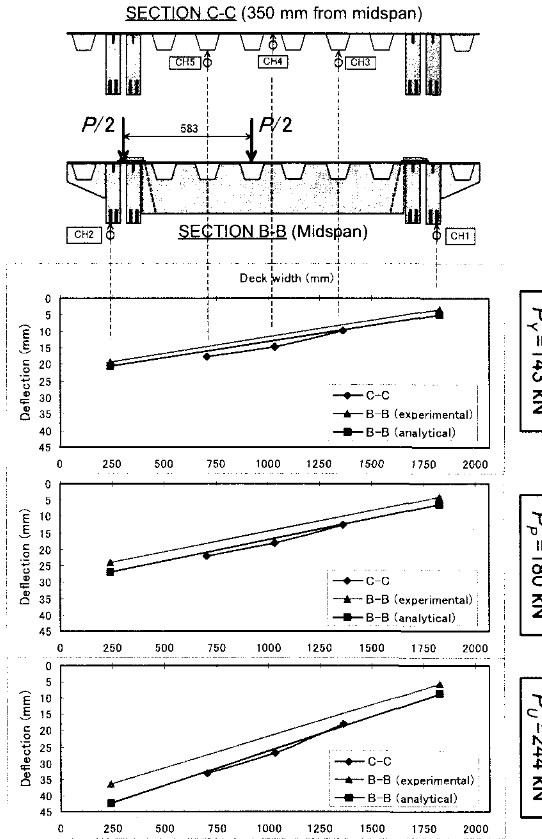

**Fig. 3 Deflection of hybrid bridge model**

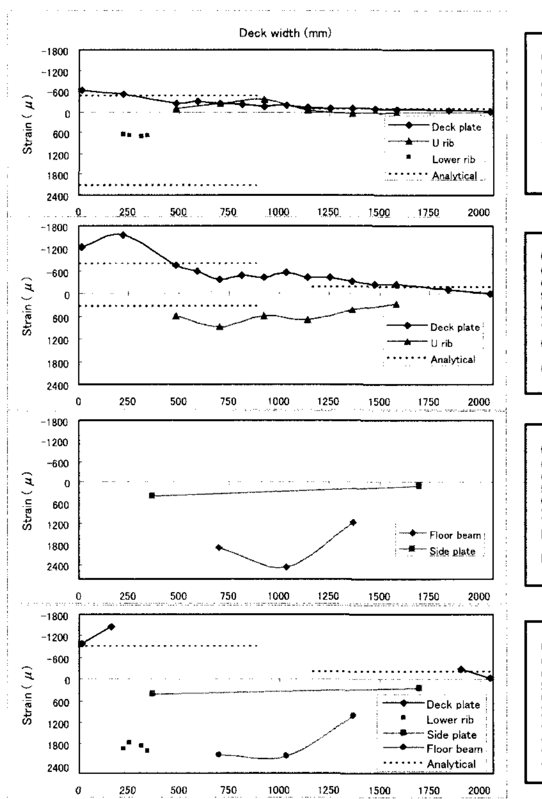

**Fig. 4 Strain state at $P_U$ (section view)**

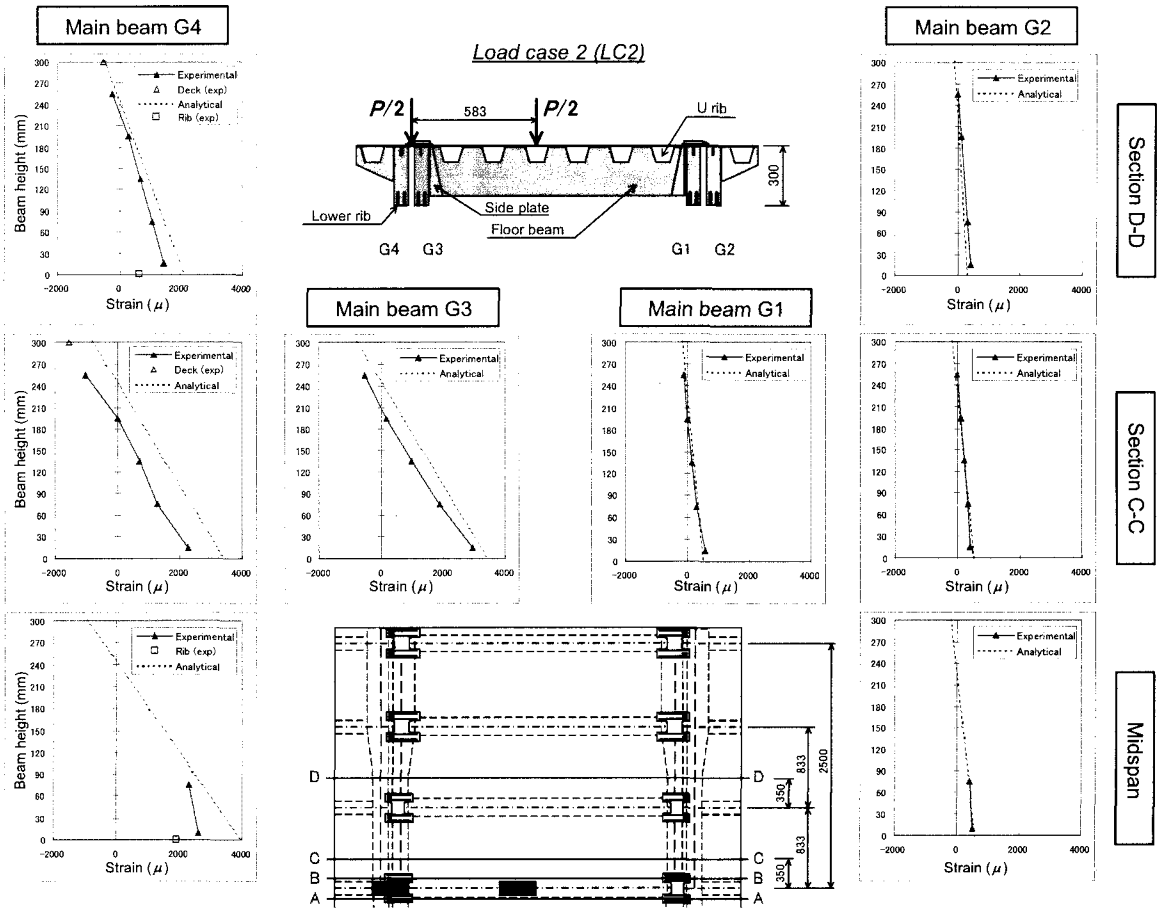


**Fig. 5 Longitudinal strain distribution of main beams at $P_U$ = 243.7 kN (lateral view)**

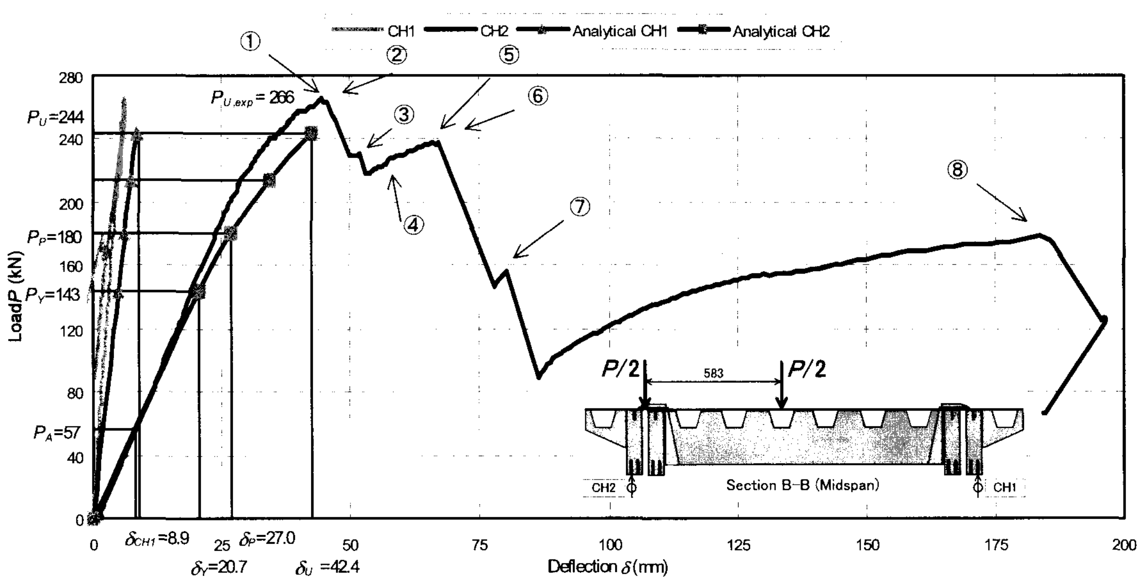


**Fig. 6 Load-displacement curves at midspan**

## 4. CONCLUSIONS AND DISCUSSIONS

A reduced scale bridge model was subjected to failure test in order to investigate the structural behavior of steel-glulam hybrid bridges and to validate the applied composite beam theory. The analytically predicted failure load was only 9% less than the experimental one, thus proving the ability of the applied theory to effectively describe the behavior of this kind of structure.

Strain distributions of structural members are assumed to be uniform and limited by the effective widths of the steel deck: they are calculated for the width $\lambda_1 + c + \lambda_2$ (see Fig.1). Due to local deformation of deck plate near loading position, a non-uniform strain distribution was observed, peak values greatly differing from the predicted ones (section C-C). Except for this and the strain of lower ribs in main beams G4 and G3, all other experimental data follow closely the analytical predictions.

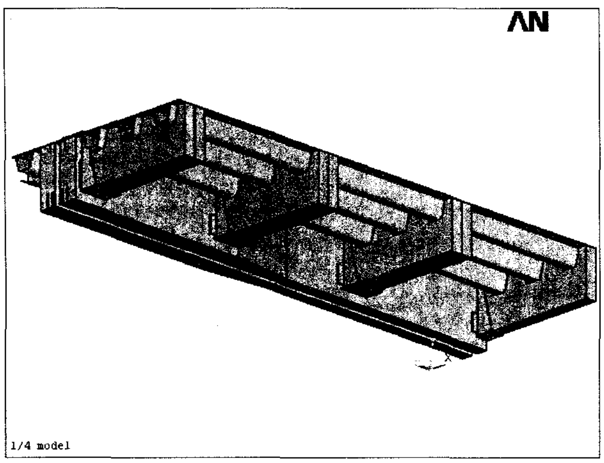


**Fig. 7 Hybrid bridge model**

However, performing a finite element analysis became desirable in order to understand more profoundly the interaction between structural members. A three-dimensional finite element model is being developed at the moment using the general-purpose nonlinear finite element program ANSYS. Due to the large size and because of double symmetry, only a quarter of the tested hybrid structure is being modeled (Fig. 7). All structural members are simulated by solid elements. Results of this analysis will be presented in a future paper. In addition to this, full-scale bending tests of double floor beam-orthotropic steel deck hybrid structure is also being performed[7].

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