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Influence of deformation due to collision on mechanical behavior of steel bridge

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ABSTRACT: The girder of an overpass bridge is found damaged by the collision of a truck running underneath occasionally. The influence of the damage on the mechanical behavior of the bridge has to be evaluated for the safety of traffic on the overpass. Yet it is not always an easy task, since the mechanical behavior of a deformed girder has not been studied much. One of the authors has been involved in the safety evaluation of a steel girder bridge damaged by collision. The bridge consisted of two steel main-girders, and one of them was badly damaged. In the present study, making use of the information on the actual damage, the collision load is estimated by the finite element analysis and the deformation of the main girder is reproduced. The bending behaviors of the intact girder, the girder damaged by collision, the girder with larger damage are then studied numerically. The results indicate that the damage influences the bending behavior, but the reduction in the bending capacity is limited even when the deformation is quite large.

1 INTRODUCTION

From time to time, an overpass bridge damaged apparently by the collision of a truck is found. Some of those bridges are presented in Figure 1. They are all in the region where the authors’ institute is located.

The construction of railways preceded that of highways in Japan. Therefore, the clearances under quite a few railway bridges do not satisfy the current requirement, which seems to lead to more collisions of trucks with railway bridges. Some technical reports on collision damage in railway bridges are available in the literature, for example Nieda & Suzuki (2000), Suginoue et al. (2006) and Nakayama et al. (2008)among others. Most of those technical papers describe only the damage and the first-aid measure employed without touching on the safety issues such as the influence on the load-carrying capacity. The investigation by Nakayama et al. (2008)is one of a very few studies on the influence of collision damage on the load-carrying capacity of the damaged main girder.

Nakayama et al.(2008) first studied the characteristics of collision damage in the steel railway bridge. They stated that out of 14 damaged bridges, eight bridges were subjected to severe damage such as the deformation of track, the fall from the bearing and crack in the main girder, which have resulted in the immediate closure of those railway bridges. The remaining six girders underwent only the deformation of the main girders. The major damages of those six girders were classified into three groups: local upward deformation of the lower flange, horizontal deformation of the lower flange and the combination of the two. Focusing on the damages of the first two groups, Nakayama et al. have investigated the load-carrying capacity of the deformed girder experimentally and numerically. To that end, they prepared three girder specimens. The span of each girder was 5360 mm long and the difference between the three girder specimens lies in the initial deformation: one had no initial deformation, another girder had a locally upward displacement of the lower flange up to 78 mm and the lower flange of the other girder was displaced horizontally up to 27 mm. These initial deformations were decided referring to the maximum values they observed in the actual railway bridges damaged by collision. Their research results have revealed that the damages they considered have insignificant influence on the load-carrying capacity. They have observed the tendency that the collision even increased the capacity. They stated that a possible reason for this phenomenon was the strain-hardening due to the deformation caused by the collision.

The first author has been involved in the safety evaluation of a highway steel bridge damaged by collision. The damages of the main girders were severer than the one investigated by Nakayama et al. (2008). Yet no cracks in the girder and no significant damage around the bearings were found. The main concern was therefore the load-carrying capacity of the damaged girder. The present paper deals with this issue.

Figure 1. Bridges damaged by collision.

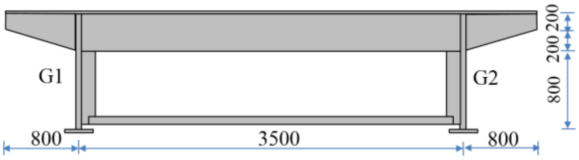

Figure 2. Cross section, dimensions are in mm.

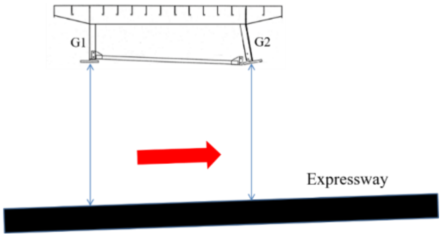

Figure 3. Schematic of deformation.

2 BRIDGE INFORMATION

The damaged highway bridge to be studied is a single-span steel girder bridge. The bridge is 29.8 m long and the span is 29 m long. The superstructure consists of two main girders, G1 and G2, and orthotropic deck. The main girder has transverse stiffeners while the orthotropic deck has longitudinal stiffeners and cross girders. Lateral struts are installed to support two pipes. This is not a big bridge and it carries only one lane for a specific direction. The cross section of the bridge is shown in Figure 2.There is another bridge right next to this bridge. This bridge serves traffic in the opposite direction and was not subjected to collision damage at all.

3 COLLISION DAMAGE

Only one of the main girders, G2, was found damaged. This is because the expressway below the bridge is uphill. The lower flange and the web were displaced outward, as is shown schematically in Figure 3. The cross girders set in the upper part of the web restricted the web deformation only to the lower part. The residual horizontal displacements of the lower flange of G2 were measured, the results of which are presented in Figure 4.

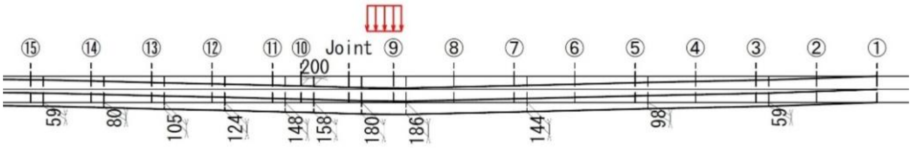

Figure 4. Residual horizontal displacement of lower flange.

(a) (b) (c)

Figure 5. Damages due to collision (a) Bent transverse-stiffeners and strut separated from stiffener (b) Buckled transverse-stiffener (c) Transverse stiffener separated from web.

29 transverse stiffeners are welded to each web in addition to those at the locations of the bearings. The cross section having the transverse stiffener is given the number; the section closest to the abutment A2 is Section 1 and the section closest to the abutment A1 is Section 29. The circled numbers in Figure 4 correspond to those section numbers.

Figure 4 indicates that the largest horizontal displacement was caused around Section 9, which is 8.8 m away from the A2 bearing. A truck must have collided with around Section 9. The displacement measured at the point closest to Section 9 is 186 mm, which is 1/156 of the span length. Note that the displacement of the girder studied by Nakayama et al. (2008) is 1/199 of the span length and that the Japanese design specifications (2017) requires the initial deflection to be less than 1/1000 of the member length. The displacement of the present bridge is quite large.

The deformation of the main-girder web and the lower flange are not the only damage. In addition to them, some transverse stiffeners were bent and/or buckled; some welded connections between the transverse stiffeners and the web were fractured, separating the transverse stiffeners from the web; and some bolted connections between the transverse stiffeners and the lateral struts were broken, separating the lateral struts from the transverse stiffeners. Those damages are can be observed in Figure 5.

4 DAMAGE REPRODUCTION

It was observed that the lateral strut at Section 11 was separated from the transverse stiffener and that it was held between the two main girders. Since the residual horizontal displacement at Section 11 is just about 148 mm, the phenomenon can be created if and only if the maximum horizontal displacement of the lower flange at Section 11 due to the collision is equal to or greater than 148 mm while the residual displacement would be smaller than 148 mm if not for the lateral strut at Section 11.

Figure 6. Finite element mesh.

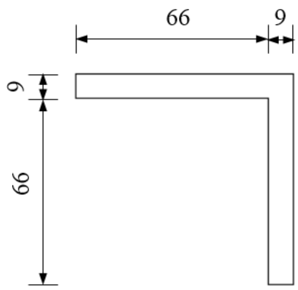

Figure 7. Cross section of lateral strut.

Herein the static load that can cause the above situation is estimated by the finite element analysis that takes into account the material and geometrical nonlinearities. This load has the effect virtually equivalent to the collision and so it is called the collision load in this study. For this analysis, ABAQUS (2013) is used. Shell elements are employed for all the members except for the lateral struts that are modeled by beam elements. The finite element mesh is shown in Figure 6.

Steel used for the bridge is SM490Y specified in Japan Industrial Standard. Young's modulus E is 200 GPa and Poisson's ratio 0.3. Yield stress is 365 N/mm^2 for the plate thickness t less than 16 mm and 355 N/mm^2

for 16 mm≤ t< 40 mm. Beyond the yield stress, the material stiffness is assumed to be E/100. The elastic-plastic behavior of von Mises type with the kinematic hardening rule is assumed.

As noted earlier, the largest horizontal displacement was found around Section 9 (Figure 4). The coating on the bottom surface of the lower flange was scratched out near Section 9. It is then legitimate to conclude that the collision occurred in this portion.

In the present study, based on the observation of the scratch on the coating of the lower flange, the collision load is assumed to be the uniformly distributed load over 540-mm range, as the red arrows in Figure 4 indicate. The lateral strut at Section 11 was found bent with the maximum deflection of 8 mm. The lateral strut is 3200 mm long and the cross section is shown in Figure 7. The finite element analysis of this member under axial load is conducted using shell elements. The axial load that causes the 8-mm deflection turn out 41 kN. The bridge is then analyzed by applying the distributed load around Section 9 together with the point load of 41 kN, the reaction from the lateral strut, at the lower flange of Section 11.

Under this loading condition, several nonlinear analyses are conducted and it is found that once the distributed load is increased up to 1587 N/mm, the total removal of the load leaves the horizontal displacement of 148 mm at Section 11. Therefore, 1587 N/mm can be considered the collision load.

The computed residual horizontal displacement of the lower flange is plotted together with the measured displacement in Figure 8. Fairly good agreement is observed. The collision load 1587 N/mm is distributed over 540 mm, the total of which amounts to 857 kN. This value is comparable to the design collision load of 1000 kN. These observations validate the present analysis.

5 MECHANICAL BEHAVIOR OF DEFORMED GIRDER

To evaluate the influence of the damage caused by the collision, the bending capacity of the damaged girder by itself is obtained by the nonlinear finite element analysis. The girder to be analyzed here is taken out of the bridge deformed by the collision load in the previous section. The orthotropic deck of the effective width is included in this girder model (Figure 9).

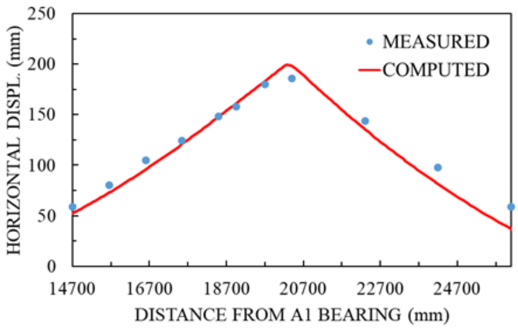

Figure 8. Residual horizontal displacement of lower flange.

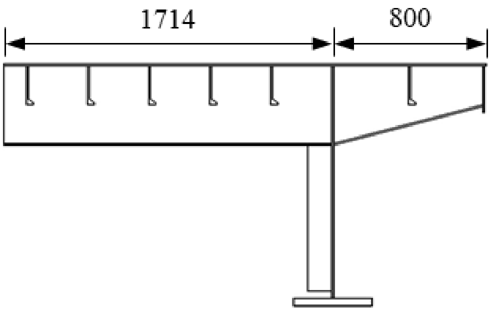

Figure 9. Cross section of girder to be analyzed.

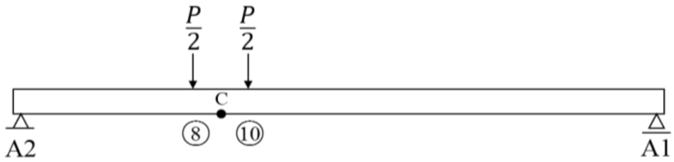

Figure 10. Loading condition.

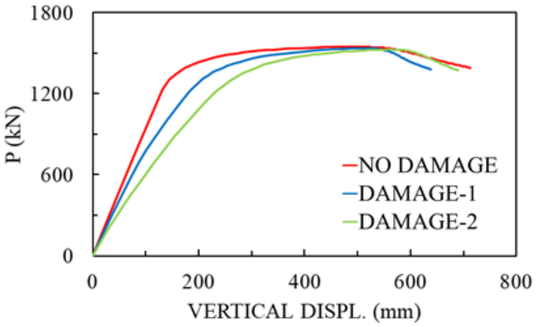

Figure 11. Load P - vertical displacement relationship at Point C.

The girder is simply supported. The out-of-plane displacement, the rotation around the vertical axis and the rotation around the girder axis (torsion) are constrained at the top of the web. As shown in Figure 10, two point-loads are applied at the top ends of Sections 8 and 10, as the severest damage is around Section 9. Point C is located at the bottom of the web at the center between Sections 8 and 10. To quantify the influence of the damage, the intact girder is also analyzed.

The numerical result in terms of the load P and the vertical displacement at Point C is presented in Figure 11. The mechanical behavior of the girder damaged by the collision is given as DAMAGE-1, while that of the intact girder is as NO DAMAGE. The results indicate that the initial stiffness is reduced by 14%. Unlike the case of Nakayama et al. (2008), the maximum load doesn't increase. It decreases instead, yet the reduction is merely 0.8%, from 1548 kN to 1536 kN.

To further investigate the influence of the damage, the residual horizontal displacement is increased by a factor of 1.5: the maximum horizontal displacement is then 1/104 of the span length. The same analysis as above is conducted and the result is shown as DAMAGE-2 in Figure 11. The reduction in the initial stiffness now becomes 31%. Yet the reduction in the maximum load is still rather small, which is only 1.3%, from 1548 kN to1528 kN.

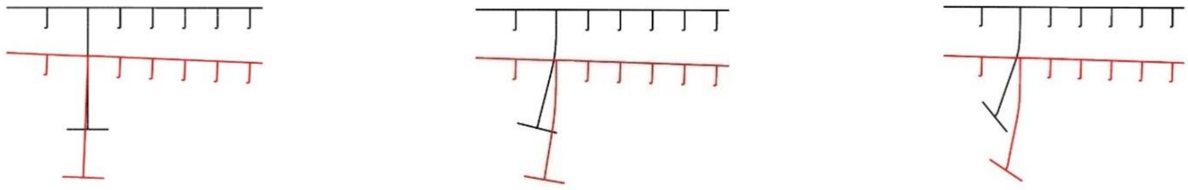
(a) (b) (c)

Figure 12. Deformed configuration of girder (a) no damage (b) damage-1 (c) damage-2.

The deformation of the girder is given in Figure 12. The black figure is the cross section before loading. The red figure is the deformed configuration at the maximum load. The vertical displacement is dominant in case of the intact girder as it should. On the other hand, the horizontal displacement is also significant in the damaged girders: they tend to deform in the way that reduces the horizontal residual displacement. The damage due to collision thus changes the deformation characteristic of the girder considerably.

6 CONCLUDING REMARKS

The influence of the collision on the deformation of the steel girder bridge was studied. Through the nonlinear finite element analysis, the collision load was identified first, which gives the residual horizontal displacement of the lower flange caused by collision fairly well. Using the damaged girder reproduced by the finite element analysis, the influence of the damage due to the collision was then investigated. The result indicates that while the initial stiffness is reduced by 14%, the decrease in the bending strength is merely 0.8%. Even when the damage is made 1.5 times larger, while the influence of the collision damage on the initial stiffness becomes large, the influence on the bending capacity remains small: the reduction is only 1.3%. This phenomenon may be attributable to that the damaged girder behaves in a quite different way from that of the intact girder.

It may be then stated that the deformation of the girder doesn't necessarily threaten the safety of the bridge immediately. However, it needs paying attention to that the influence of the deformation on the stiffness of the girder is large compared with the bending capacity. It is also noteworthy that the damage other than deformation, if found, could lead to considerable reduction in safety.

ACKNOWLEDGEMENTS

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