Evaluation of dynamic collapse in thin-walled composite members

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Abstract. Many of steel thin wall closed section members are used by automobile industry. The local buckling of these elements that occur under compressive stress remains the main technological problem. To improve the performance of the members, the filling the inside of closed section with the low-density foaming material are usually used. In this study, we present the usefulness of axial compression and 3-point bending tests for the composite members filled with two kinds of epoxy resin. The difference between composite member and thin-walled member was investigated concerning their elastic and plastic collapse characteristics while tested with various deformation velocities. The adherent strength between thin-walled member and foaming material, and filling effect of the foaming material in the energy absorption characteristics was clarified.

1. Introduction

Steel thin wall closed section member is mainly used for traffic applications (e.g., automobile). The main problem here is a local buckling under compressive stress that was already thoroughly investigated [1-4]. To resolve this problem, the elements filled with the low-density foaming material are used nowadays [5-8]. In this report, we call such a member the “thin-walled composite member” or “composite member” in short. Recently, it was found that the filling effect is useful for cost and performance improvement [9,10]. The advantages of thin-walled composite member include: increase of yield load, elastic rigidity and loading-plateau in plastic region. Composite member exhibit high strength, improved rigidity and enhanced energy absorption in the plastic region. However, homogeneity and stability of the foaming in the closed section appears here the main obstacle due to employment of the polymer material [6]. Therefore, mechanical properties of the foaming material are seem very unstable, and the adherent strength, synthesis characteristics and deformation velocity dependence, remain here unsolved issue. Consequently, it is necessity of independent examination of these construction elements [11].

The aim of the present paper is to reveal the difference of thin-walled member and composite member under the dynamic compression loading. As a test piece, we used two kinds of composite member filled with the foaming material of the different density for the hat type thin-walled cross section member. Axial compression and 3-point bending tests were carried out on the composite member, the hat type thin-walled member and the epoxy resin foaming material. The difference in
adherent strength and the energy absorption of composite member and thin-walled member was carefully investigated from the point of view of elasticity and plastic collapse at various deformation velocities.

2. Experimental

2.1. Test pieces
The thin-walled member contains the hat type made of cold rolled steel sheet, SPCC, as shown in Figure 1(a). The foaming material - thermosetting epoxy resin (figure1(b)) was prepared by multiple foaming procedure: 2 times foaming material, specific gravity 0.77g/cm³ and 3 times foaming material, specific gravity 0.55g/cm³. The composite member filled the hat type thin-walled member with 2 and 3 times foamed material (figure 1(c)). The foam – steel interface was adhered by filling. Constitution of the foaming material, specification of the test pieces and test conditions are given in tables 1, 2 and 3, respectively.

Figure 1. Test pieces for axial compression and 3-point bending tests.

Table 1. Constitution of foaming material.

| Material                   | Weight ratio (%) | Material                   | Weight ratio (%) |
|----------------------------|------------------|----------------------------|------------------|
| Epoxy resin                | 34.5             | Carbon black              | 1.6              |
| Synthetic rubber           | 8.1              | Increasing agent          | 45.8             |
| Thermoplastic elastomers   | 5.8              | Hardening agent / accelerator | 2.6            |
| Foaming agent              | 1.6              | Total                      | 100              |

Table 2. Specification of test piece.

| Test piece                | Foam Two times* | Three times* | Thin-walled member (Hat type) |
|---------------------------|-----------------|--------------|-------------------------------|
| Cross-section area $A$    | $2.40 \times 10^{-3}$ (m²) | $2.24 \times 10^{-2}$ (m²) |
| Young’s modulus $E$       | 1.14 (GPa)      | 659 (MPa)    | 206 (GPa)                     |
| Moment of inertia of cross-section area $I$ | $3.20 \times 10^{-7}$ (m⁴) | $6.78 \times 10^{-6}$ (m⁴) |
| Yield stress $\sigma_Y$   | 13.7 (MPa)      | 7.73 (MPa)   | 288 (MPa)                     |
| Ultimate tensile stress $\sigma_U$ | 14.9 (MPa) | 8.54 (MPa) | 394 (MPa)                     |

*The result as length of member is 100mm.

Table 3. Types of test piece and test.

| Test piece                | Foaming material | Thin-walled member | Composite member |
|---------------------------|------------------|--------------------|------------------|
| Length of member          | 25, 50, 100, 200, 400mm, 500mm | 400mm, 500mm | (only bending test) |
| Type of test              | Axial compression, Three-point bending (span 400mm) | | |
| Deformation velocity      | 0.05mm/s, 5mm/s, 400mm/s | | |
| Foaming rate              | Two times (0.77g/cm³), Three times (0.55g/cm³) | | (Relative density of foaming material) |
2.2. Experimental procedure

Axial compression test and three-point bending test, as shown in Figure 3, were carried out using the hydraulic dynamic testing machine (Figure 2). The maximum displacement in the axial compression test was 150 mm on the thin-walled member and composite member, and a 50% of the member length on the foaming material. The three-point bending test concerned, the maximum displacement, and the contact radius at loading and supporting point were 50 mm, 5 mm and 1.5 mm, respectively. The employed deformation velocity equaled 0.05 mm/s, 5 mm/s and 400 mm/s during our experiments.

2.3. Experimental result

In the axial compression test (Figure 4), the maximum load in the composite member was increased due to the "filling effect". For example, maximum load of the 2 times foaming material (36 kN) are 1.8 times for maximum load of the 3 times foaming material (20 kN). Furthermore, the maximum load of the composite member (48 kN) which filled the thin-walled member with the 3 times foaming material increased about 1.8 times for that of the thin-walled member (27 kN). However, in composite member which filled the 2 times foaming material, maximum load (44 kN) increased about 1.6 times. We attribute the observed effect to peeling generated at the interface of the constructional member (thin-walled and 2 times foaming) as well as to the rigidity of the composite member lowered.

The loading history of composite member, as shown in Figure 4, fluctuates with displacement, after it reaches the maximum load. Plastic buckling deformation of the thin-walled member by the axial compression load is difficult to generate, because the foaming material is inside the rigid structure, something described in section 5.3. The thin-walled part of composite member is deformed outside the member by the pressure of the inside foaming material. The interface of thin-walled member and foaming material is adhered by the filling, and the rigidity of the member increases. We consider that the fluctuation behaviour becomes prominent due to these deformation constrains. Moreover, the three-point bending test (Figure 5) confirmed the effect of filling on construction strength.
Maximum load $P_{\text{max}}$ was carefully recorded for all values of strain rate in the axial compression test (figure 6). The strain rate was determined by dividing deformation velocity (0.05, 5, 400 mm/s) by the length of member (foaming material: 100 mm, thin-walled and composite member: 400 mm).

3. Adherent strength

Filling effect became evident from our comparison of maximum loads. Insertion of the foaming material was made in order to examine the effect of filling-member adherence. Using insertion composite member without the adherent strength, the axial compression test and three-point bending...
test were carried out, and the results compared with that of the composite member (compare figures 4 and 5).

One can notice the maximum loads 0.6 times higher for foaming material, and 0.7 times in the another specimen (refer to figure 4). In the case of the thin-walled member, maximum loads were about 1.0 to 1.1 times in the 3 and 2 times foaming materials. The maximum load does not increase by the insertion of the foaming into thin-walled member, though there is the possibility of generation of the frictional force during loading. Thus, the adherence by the filling results in improved strength. In the 3-point bending test (figure 5), the foaming material in the insertion composite member was fractured during the deformation, which cased load-drop. The displacement of fracture was same as during to the test result for the foamed material (about 5.4mm at 2 times foaming material). Thus, in both of axial compression and three-point bending tests, the maximum load of composite member filled the foaming material inside is higher than that of composite member inserted the foaming material inside, which clarifies the effect of the adherent strength.

4. Characteristics of energy absorption

Energy absorption and its dependence of strain rate were examined as shown in figure 7. The relationship between energy absorption and curvature change speed of each member was examined in the three-point bending test. The curvature change speed was calculated by dividing curvature of the member which generated by displacement δ by the time. The curvature was calculated from equation \( \kappa = \frac{4\delta}{l^2} \) [12], where \( l \) defines span (400mm).

In the axial compression test, the energy absorption of composite member increased about 1.1 times (on both of 2 and 3 times) for that of insertion composite member. In addition, the energy absorption of insertion composite member increased about 3.8 times (2 times) and about 3.0 times (3 times) for that of thin-walled member. The energy absorption of composite member also increased about 1.5 times (2 times) and about 1.4 times (3 times) for that of thin-walled member. The energy absorption of insertion composite member increased about 1.5 times (2 times) and about 1.2 times (3 times) for that of thin-walled member.

![Figure 7. Characteristic of energy absorption on axial compression test. The symbol condition is the same as figure 6.](image)

![Figure 8. Characteristic of energy absorption on three-point bending test. The symbol condition is the same as figure 6.](image)
Although our experiment explores low strain rate range, the strain rate dependence was noted (figure 6). Strain rate dependence on energy absorption is shown in figure 7, while the energy absorption increases linearly in the whole strain rate range. The energy absorption is generated by deformation resistance in the whole plastic region and it increases linearly, since viscous resistance (the plastic flow stress) in plastic region remains constant [13]. In the three-point bending test (figure 8), the energy absorption of composite member have an effect on the deformation velocity, and it increases almost linearly, in spite of that of the foaming independent of deformation velocity. Thus, the foaming does not affect strength and plastic deformation resistance in the thin-walled member.

5. Plastic collapse characteristics of each member

5.1. Plastic collapse of foaming material

In axial compression test of the foaming material, the collapse was investigated for 5 kinds of member length (see Table 3). The maximum load of the foaming material decreased with the member length (figure 9). The foaming material collapsed due to shearing stress (see figure 10②, ③). In this experiment, the axial angle with normal line concerning this shear collapse was 40 to 45 degree. The edge in surface of collapse by shearing stress contacts the surface which gives the load on the base and load cell in the equipment, when the member length is short such as 50 and 100mm. The maximum load seemed to increase, since a shear collapse is restricted by this friction. In the case of member length 100 and 200mm, the maximum load did not change. The buckling deformation was generated in the member, and it collapsed by the bending in the centre of the member, in member length 400mm. Though the 400mm length member should be considered the middle column, because the slenderness ratio is about 35, the Euler’s buckling load was calculated with 13kN, when it was assumed both free end for the confirmation, and this value was closed to the experimental result (15.4kN). The bending stress takes maximum value at the central of the member length, and the crack is generated in the tension side surface, by the bending deformation supported at both end. It is considered that the crack was propagated perpendicularly to the loading direction by the bending deformation, and that the member was collapsed by it (as the example, shown in figure 11).

5.2. Plastic collapse characteristics of thin-walled member

When thin-walled member undergoes progressive plastic buckling, (1) hat type plate and thin plate are deformed between the spot welding points, as shown at arrow⑤ in figure 12B. Further, (2) side wall of member shown at arrow⑥ is deformed to the thin-walled member inside, and (3) surface part of member shown at arrow⑦ is also deformed to the member inside, similarly with the side wall. The deformation of these (1) to (3) is generated simultaneously. This deformation is terminated at figure 12A ⑤ and ⑥, and the similar deformation is generated after ⑥ continuously, then it is finished at ⑩. By repeating this deformation, the thin-walled member progressively generates plastic buckling.

![Figure 9. Load-displacement curve for epoxy resin foaming materials. Load of each 3 times foaming material on 5mm/s deformation velocity was examined on the dependence of displacement.](image-url)
5.3. Plastic collapse characteristics of composite member
The collapse characteristics of composite member (figure 13) are dependent on the collapse mode of thin-walled member. Deformation process of the composite member is similar to the thin-walled member. However, in case of the thin-walled member, the surface part (figure 12B○) was deformed. However, the surface part of composite member could not be deformed to the member subject inside and are pushed outside, since the foaming material is filled inside. The side wall of member (figure 12B⑬) also could not be deformed inside by the effect of the foaming material. Moreover, by the adherence of foaming material and thin-walled member, the strength of the composite member was improved.

6. Conclusion
This study, clarify the difference in mechanical characteristics of the thin-walled composite member and the constructional member, axial compression and 3-point bending tests were carried out on the composite member which is filled 2 kinds of epoxy resin foaming material in hat type thin-walled cross section member. The adherent strength between thin-walled member and foaming material was clarified by comparing the strength of insertion composite member and filling composite member. The energy absorption improved by filling the member inside with the foaming material.

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Figure 12. Collapse of thin-walled member. These figures shows the sequence photographs (δ=4mm (0.8s/1Frame)) of deformation of the thin-walled member in case of 5mm/s deformation velocity.

Figure 13. Collapse of composite member. These figures shows the sequence photographs (δ=5mm (1s/1Frame)) of deformation of the 3 times composite member in case of 5mm/s deformation velocity.

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