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ULTIMATE TENSILE STRENGTH OF 780MPA-GRADE AND 590MPA-GRADE H-SHAPED STEEL MEMBERS JOINTED WITH HIGH-STRENGTH BOLTS

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SUMMARY

In order to investigate the effects of bolt-hole arrangement and edge distance of bolted joints on the ultimate tensile strength and failure modes of H-shaped tension members, we conducted tension tests of the H-shaped members jointed with high-strength bolts. Newly developed 780Mpa-grade and 590Mpa-grade high-quality steels, which had low yield ratios, were used for test specimens. We proposed formulas to predict the ultimate tensile strength of flanges and webs for tearing fracture and end fracture. The experimental results confirmed that the ultimate strength of the H-shaped member was obtained by the sum of both strength of flange and web. The ultimate strength of the prediction formulas, which had been previously obtained from the steel plate joint tests, to the H-shaped members was discussed. Also, the reliability of the design formulas specified in the LSD by AIJ and the LRFD by AISC was discussed based on the experimental results.

INTRODUCTION

Newly developed 780Mpa-grade and 590Mpa-grade high-quality steels, which have low yield ratios, are beginning to be adopted in beam-columns or tension members of steel buildings. To use these new steels for tension members jointed with high-strength bolts, a clear understanding of the plastic behaviors of these joints is essential. The ultimate strength design should be such that tension members should not break at the bolted joints before a certain level of plastic deformation is attained in the members. We investigated experimentally the relationships between failure modes and ultimate tensile strength of H-shaped members jointed with high-strength bolts. It is well known that there are two failure modes of flange plates and web plates with bolted joints as shown in Fig. 1: tearing fracture and end fracture. We examined the effects of bolt-hole arrangements and edge distances of flanges and webs on the ultimate strength and the two failure modes. In the first stage experiments, tension tests of H-shaped members, in which only flanges or webs were jointed with high-strength bolts, were performed. We clarified the individual relationships between the ultimate strength and the failure modes of the flanges and webs, and derived the prediction formulas of the ultimate strength of the flanges and webs for each failure mode. In the second stage experiments, H-shaped tension members, in which both the flanges and webs were jointed, were tested, and their ultimate strength and failure modes were clarified. Based on the results of these two-stage experiments, the sum of the experimental or predicted ultimate strengths of the flange and web was compared, respectively, with the experimental ultimate strength of an H-shaped member with bolted joints both in the flange and web. In the experiments, in order to investigate differences in the prediction formulas of the ultimate strength between the above new steels and the conventional 400Mpa-grade steel, the same kind of tension tests as applied for the new steels were carried out for 400Mpa-grade steel as well. Furthermore, the prediction formulas of the ultimate strength of the steel plates for the three failure modes, which had previously been obtained by the authors, were compared with the formulas for the flanges and webs [UDAGAWA and YAMADA, 1998]. Also, the reliability of the design formulas specified in the LSD by AIJ [Architectural Institute of Japan, 1998] and the LRFD by AISC [American Institute of Steel Construction, 1986] was discussed based on the test results.

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EXPERIMENT

Test specimen

A section of H-250x150x7x10 (mm) was adopted for the H-shaped members in the experiments as shown in Fig. 2. Three kinds of specimens were made, in which only flanges or webs were jointed with high-strength bolts (hereafter referred to as flange-joint specimen and web-joint specimen, respectively) and both the flange and web were jointed (referred to as flange-web-joint specimen). Figure 2 shows the test specimen with a flange bolt-hole arrangement of 2 rows and 3 lines (referred to as 2x3) and a web bolt-hole arrangement of 4x1. The following bolt-hole arrangements were used: 2x2 and 2x3 for the flanges and 3x1, 3x2, 3x3, 4x1 and 4x2 for the webs. Ultrahigh-strength bolts (M16) made of maraging steel were used to avoid bolt breakage in the tests. The diameter and pitch of the bolt holes were 18mm and 40mm, respectively. The edge distance e_1 and e_2 and gage distance g of the flanges and webs are shown in Fig. 3 and their measured dimensions are given in Table 1. In Table 1, d denotes a bolt diameter of 16mm and the last numbers of the name of the specimens show the steel grades. Namely, 4, 6 and 8 indicate 400Mpa-grade, 590Mpa-grade and 780Mpa-grade steels, respectively. A total of 62 specimens were tested for three kinds of steels.

Material properties

Table 2 shows the yield points, tensile strengths, yield ratios and elongation factors at breakage obtained from coupon tests on the 780Mpa-grade, 590Mpa-grade and 400Mpa-grade steels (hereafter referred to as HQ780, HQ590 and SS400 steels, respectively). The yield points of HQ780 steels were determined by the 0.2% offset method. 780Mpa-grade and 590Mpa-grade steels used in these tests were different from the current 780MPa and 590MPa high-tension steels, and have low yield ratios. Japanese steel manufactures specify a yield point in the range of 6.30 to 7.25 tf/cm^2 and 4.50 to 5.50 tf/cm^2, a tensile strength in the range of 7.60 to 8.80 tf/cm^2 and 6.00 to 7.50 tf/cm^2, yield ratios of less than 0.85 and 0.80 and an elongation factor at breakage of more than 0.16 and 0.20, respectively. Although some of the 780Mpa-grade steels did not meet the specifications, the test results for these steels were included in the discussion section. In Table 2, the asterisks of F* and W* correspond to the asterisks of the specimens in Table 1 and F and W represent the flange and web, respectively.

Loading and measurement

The apparatus used for the tension test is shown in Fig. 4. The tests were conducted under nonfriction conditions at the high-strength bolt joints in order to evaluate the ultimate strength accurately. The monotonic tensile load P and axial deformation • of a section of length l were measured as shown in Fig. 4.

Experimental results

The several relationships between tensile load and axial deformation for each fracture type are shown in Fig. 5. In the figure, • indicates the maximum load. Photo 1 shows specimens fractured in each of the two modes. Table 1 shows the ultimate strength $_eP_u$, $_eP_{uf3}$ and $_eP_{uwi}$ and fracture type of each specimen. $_eP_u$ represents the maximum load of the flange-web-joint specimens. $_eP_{uf3}$ and $_eP_{uwi}$ give the maximum load of the flange-joint specimens and web-joint specimens, respectively. Failure modes•,• and • in the table represent inner tearing fracture, outer tearing fracture and end fracture, respectively.

DISCUSSION

Prediction of ultimate strength for flange-joint and web-joint specimens

We predicted the ultimate strengths of the flange plates for outer tearing fracture based on the test results of the flange-joint specimens. We also predicted the ultimate strengths of the web plates for inner tearing fracture and end fracture using the test results of the web-joint specimens. The prediction formulas were as follows:

Outer tearing fracture of flange plate $\quad {}_cP_{uf3}$ = • •uf Antf' + •f3•uf Ansf (1)

Inner tearing fracture of web plate $\quad {}_cP_{uw2}$ = • •uw Antw + •w2•uw Answ (2)

End fracture of web plate $\quad cP_{uw4} = m \bullet_{w4} \bullet_{uw} A_{nsw}$ (3)

Section areas Antf', Ansf, Antw and Answ are shown in Fig. 3 and m indicates the number of rows in the bolt hole arrangement. • in Eqs. 1 and 2 is defined as the increase coefficient of tensile strength, since the restriction of plate deformation due to the bolts increased the tensile strength at the net section. The expressions of • were previously given by the authors as follows [UDAGAWA and YAMADA, 1998]:

SS400 steel $\quad \bullet = 1.070 - 0.014$ (Antf' or Antw') / (Antf or Antw) / (m-1)

HQ590 steel $\quad \bullet = 1.088 - 0.021$ (Antf' or Antw') / (Antf or Antw) / (m-1) (4)

HQ780 steel $\quad \bullet = 1.120 - 0.027$ (Antf' or Antw') / (Antf or Antw) / (m-1)

$\bullet_{f3}$, $\bullet_{w2}$ and $\bullet_{w4}$ in Eqs. 1-3 are defined as the shear strength coefficients. For example, the coefficients $\bullet_{f3}$ for each specimen undergoing outer tearing fracture of the flange plates were calculated under the condition that the experimental ultimate strength *ePuf3* was equal to $\bullet \bullet_{uf}$ Antf' + $\bullet_{f3} \bullet_{uf}$ Ansf . Here, the values given by Eq.4 were adopted for •. The relationships between $\bullet_{f3}$ and l^0/d for each specimen are shown in Fig. 6. l^0 is shown in Fig. 3. The shear strength coefficients $\bullet_{w2}$ and $\bullet_{w4}$ for inner tearing fracture and end fracture of the web plates were obtained in the same manner. The relationships between $\bullet_{w2}$ and l^0/d, and those between $\bullet_{w4}$ and l^0/d are shown in Figs. 7 and 8, respectively. The regression lines of the relationships between $\bullet_{f3}$, $\bullet_{w2}$, $\bullet_{w4}$ and l^0/d for each fracture type are given with solid lines in the figures and expressed as follows:

SS400 steel $\quad \bullet_{f3} = 0.581 - 0.010\,(l^0/d) \quad (4< l^0/d <8)$

HQ590 steel $\quad \bullet_{f3} = 0.514 - 0.006\,(l^0/d) \quad (4< l^0/d <8)$ (5)

HQ780 steel $\quad \bullet_{f3} = 0.462 \quad (4< l^0/d <5)$

SS400 steel $\quad \bullet_{w2} = 0.608 - 0.025\,(l^0/d) \quad (1< l^0/d <7)$

HQ590 steel $\quad \bullet_{w2} = 0.608 - 0.034\,(l^0/d) \quad (1< l^0/d <7)$ (6)

HQ780 steel $\quad \bullet_{w2} = 0.467 \quad (2< l^0/d <3)$

SS400 steel $\quad \bullet_{w4} = 0.546 \quad (1< l^0/d <3)$

HQ590 steel $\quad \bullet_{w4} = 0.516 \quad (1< l^0/d <3)$ (7)

HQ780 steel $\quad \bullet_{w4} = 0.497 \quad (1< l^0/d <3)$

where, in Eqs. 5-7, the shear strength coefficients $\bullet_{f3}$, $\bullet_{w2}$ and $\bullet_{w4}$ given with the numerical values represent the average values of two or three coefficients. The ultimate strengths *cPuf3* ,*cPuw2* and *cPuw4* predicted using the formulas (Eqs. 1-3) were obtained using the above regression lines for $\bullet_{f3}$, $\bullet_{w2}$ and $\bullet_{w4}$ and •. The experimental and predicted values of the ultimate strengths were compared, as shown in Fig. 9. In the figure, the OTF, ITF and EF indicate the outer tearing fracture, inner tearing fracture and end fracture, respectively. The predicted ultimate strengths agreed well to those obtained experimentally.

Prediction of ultimate strength for flange-web-joint specimens

The sums, *ePuf3* + *ePuwi* (i =2 or 4), of the experimental ultimate strengths were compared in Fig. 10 with the experimental ultimate strengths *ePu*, which were obtained from the flange-web-joint specimens. Here, *ePuf3* and *ePuwi* were the respective ultimate strengths of the flange-joint specimens and the web-joint specimens. The bolt hole arrangements of the flange-web-joint specimens were the same as those of the flange-joint specimens or the web-joint specimens. The sums of the individual ultimate strengths of the flange and web plates were well in agreement with the ultimate strengths of the flange-web-joint specimens. The predicted ultimate strengths

$cPuf_3 + cPuwi$ of the flange-web-joint specimens were compared in Fig. 11 with their experimental ultimate strengths *ePu*. The predicted values $cPuf_3$, *cPuwi* were calculated by Eqs. 1-3 and Eqs. 4-7. The predicted ultimate strengths agreed well to the experimental ultimate strengths as shown in Fig. 11. The maximum difference between the predicted and experimental values was approximately 3% for the HQ590 steel specimens and approximately 10% for the SS400 steel specimens.

Prediction of ultimate strength using shear strength coefficients of steel plates

We previously obtained the shear strength coefficients of the tearing and end fractures for steel plates [UDAGAWA and YAMADA, 1998]. The regression lines of the shear strength coefficients for the steel plates are given by the chain lines in Figs. 6-8. In Fig. 12, the prediction ultimate strengths $cPufp_3$, *cPuwpi* of the flange-joint and web-joint specimens using the coefficients from the steel plates were compared with the experimental ultimate strengths. The prediction values for the outer tearing fracture of the flange-joint and web-joint specimens by HQ590 and HQ780 steel coincided well with most experimental values. The values for the outer tearing fracture of the flange-joint specimens made of SS400 steel were different from the experimental values. The maximum discrepancy was about 7% for the experimental value. The relationships between the prediction and experimental values with respect to the flange-web-joint specimens are shown in Fig. 13. In these flange-web-joint specimens, the prediction values of specimens made of SS400 steel were not in good agreement with the experimental values. The maximum difference of the prediction value to the experimental one was about 6%.

Ultimate strength specified in the LSD and the LRFD

Design formulas for the ultimate strength for inner tearing fracture have been proposed in the LSD and the LRFD. The design values of tearing fracture and end fracture specified in the LSD were given as Eqs. 8 and 9, respectively. The larger one of the two values obtained from Eqs. 10 and 11 was specified for inner tearing fracture in the LRFD. The four section areas (Ant, Ans, Avg and Atg) in Eqs. 10 and 11 are shown in Fig. 14 and t represents the thickness of the web plate.

LSD tearing fracture (Ant (or Ant’) + 0.5Ans)•u (8)

LSD end fracture n e_1 t•u (9)

LRFD inner tearing fracture 0.6•y Avg + •u Ant (10)

LRFD inner tearing fracture 0.6•u Ans + •y Atg (11)

The ultimate strengths of the test specimens in this study were predicted using these design formulas on the assumption that the design formulas were adaptable to 780Mpa-grade and 590Mpa-grade steel plates. These values were compared with the experimental ultimate strengths in Figs. 15-17. The design values for both the tearing fracture and the end fracture calculated using the LSD formulas agreed well with the experimental values. Most of the design values calculated using the LRFD formulas were coincident with the experimental values for the 780Mpa-grade and 590Mpa-grade steel specimens and lower for the 400Mpa-grade steel specimens than the experimentally obtained values. The design formulas specified in the LSD gave better predictions than those specified in the LRFD.

CONCLUSIONS

The following conclusions have been obtained from the results of tension tests on H-shaped members with high-strength bolted joints made of 780Mpa-grade, 590Mpa-grade and 400Mpa-grade steels. 1) We proposed accurate formulas to predict the individual ultimate strengths of the flanges and webs for the tearing fracture and the end fracture. 2) There were slight differences in the coefficients among the prediction formulas for the 780Mpa-grade, 590Mpa-grade and 400Mpa-grade steels. 3) The ultimate strength of H-shaped tension members with bolted joints in only the flanges or webs were predicted well by the predicted formulas. 4) The ultimate strengths of H-shaped tension members with bolted joints in both flange and web were well estimated by the sum of the individual predicted ultimate strengths of the flange and web with the same bolt-hole arrangement as that of the flange and web of the H-shaped members. 5) It was possible to predict the ultimate strength of bolted joints of the H-shaped tension members using the shear strength coefficients of the steel plates, which had previously been obtained for the above three steels by the authors. 6) The ultimate strengths by the LSD design formulas were in good agreement with the experimental values for the tearing fracture and the end fracture. 7) When the values calculated using the design formulas specified in the LRFD were compared with the experimental values of the inner tearing fractures of the webs, the LRFD formulas underestimated the ultimate strengths of the 400Mpa-grade steel joints and estimated the reasonable values for the 780Mpa-grade and 590Mpa-grade steel joints.

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