A DESIGN SCHEME OF STEEL CONNECTIONS FOR PREVENTING BRITTLE FRACTURE

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SUMMARY

After 1994 Northridge and 1995 Hyougoken-nanbu earthquakes, a great deal of experimental works have been carried out. We have been able to have ample knowledge from the experiments as well as many findings among literatures in the fracture mechanics field. The authors propose, in this paper, a design scheme to produce reliable connections even under severe earthquakes. There might be many factors controlling the initiation of fracture. Among them major factors must be the fracture toughness of steels, the sizes and the shapes of notches and the strain concentration around the notches. From the practical viewpoint of design, however, most of the factors are not been clearly aware to designers beforehand. Only an exception is the fracture toughness of the steels. The structural designers can choose suitable steels with the adequate fracture toughness. Here, the authors take a typical type of welded connection of a square hollow section column and H-shaped beams, which is widely used in Japan. And we assume the connection is well fabricated following the recommended details and welding procedure. Under these limited application though, utilizing knowledge on the fracture toughness develops the design scheme. The adequacy of the scheme is examined comparing with the experimental results.

INTRODUCTION

After two severe earthquakes, a great deal of tests has been carried out. We learned many factors, which may cause fracture of steel structures, particularly fracture around welded connections. In addition, we found many achievements on the fracture problem among literatures in the fracture mechanics field. Nevertheless, very few papers discussed how to design welded connections avoiding the premature fracture during earthquakes. The authors try, in this paper, to demonstrate a design way in order to realize a reliable connection utilizing knowledge from past experiments. They are aiming at a practical design way for practitioners' use.

2. DESIGN PROCEDURE PROPOSED

2.1 Required Ductility

It is widely known in the seismic design that structures must absorb the input energy due to a severe earthquake by converting it into the plastic strain energy. Therefore, the structure must have enough deformation capacity (ductility). In the design procedure, structural designers first want to know how much the structure be expected to have it. The recent dynamic analysis of medium-rise moment frames shows us the required amount of ductility under a specified intensity of earthquake motion[Inoue et al. 1999]. Fig.1 shows its typical results. The required rotation angles of the beams are presented against the maximum values of the pseudo-velocities of earthquake motions. The columns are assumed to be within the elastic limit in the analysis. The yield strength of the frames is set to be 0.3 of the maximum elastic response as the base shear forces. We can know the required value of rotation angle of the beams for a specified intensity of the seismic load and utilize it for design of the beam-to-column connections.

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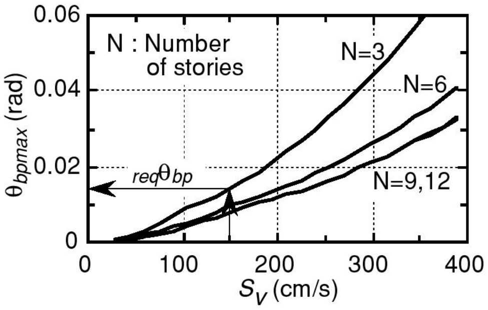
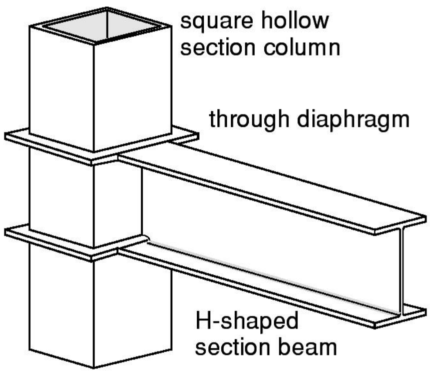


Figure 1: Required rotation angle of beam vs. pseudo-velocity of earthquake motion

2.2 Beam-to-Column Connections for Design

The connection discussed in this paper is limited to the connection of a square hollow section column and a H-shaped section beam. A typical type of the connection is shown in Fig.2, which is widely used in the moment frames in Japan. The flange plates of the beam are welded to the through diaphragms crossing the column section, while the web plate of the beam is welded or bolted to the column surface. Our problem is how to design a reliable weld joint of the flange. For this purpose, we must first evaluate accurately the flange force, which is acting on the weld joint, associated with the required rotation angle of the beam. The evaluation needs the plastic analysis taking into account a non-effective region of the web plate. The results of the analysis are presented in Fig.3. The maximum flange force Pf in the vertical axis, as expressed in a non-dimensional form, Pf / Pu (Pu= u Af: u = the tensile strength of the steel, Af = the section area of a flange), can be evaluated according to the required rotation angle bp in the horizontal axis, depending on the yield ratio YR of the steel. The detail of the analysis is described in Appendix II.



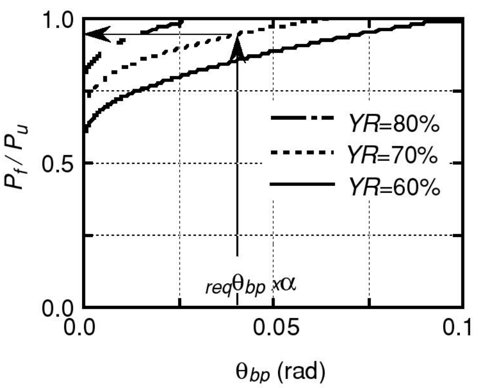


Figure 2: Typical type of beam-to-column connections

Figure 3: Flange force vs. plastic end rotation angle of beam relationships

2.3 Expected Strength of Weld Joint

In the preceding articles, it is shown to be possible to evaluate the rotation angle required for resisting against a specified level of earthquake intensity, and then the flange force acting on the weld joint associated with the required rotation angle. The strength of the weld between the flange and the diaphragm must be greater than the flange force as far as possible. It is well known that the weld strength is influenced with the quality of weld, fabrication and steel, the base metal. As the quality of the weld and the fabrication is much depending on the detailing of connection and fabrication procedure, the authors assume that designers choose a preferable connection details as shown in Fig.A1.2(b) in Appendix I, where a connection detail was selected among several other details, referring to the performance examined in the experiments. These connection details in Appendix I must be fabricated under the well-controlled procedure. Thus, the authors can focus their discussions on the factor left, the quality of steels.

It is known that the fracture toughness of the steel is the most important factor controlling the premature fracture. The authors carried out recently a series of tension tests on the specimens including the weld joint. A surface notch is intentionally provided at the end of the weld bead. The test parameters are the quality of steels, the size of the notch, the loading speed and the test temperature. These will affect the fracture toughness of the specimens. The fracture toughness was evaluated by the Charpy V-notch test. The energy absorption measured in the Charpy test is considered as an efficient index to indicate the fracture toughness, in spite that the Charpy test is easily conducted in a relatively low cost. The test is described more in detail in Appendix III.

The test results are summarized in Fig. 4. The maximum strength measured at fracture is plotted against the energy absorption vEbr for each test. The energy was evaluated by the Charpy test on the specimen taken from the vicinity of the spot from where the fracture initiated. The figure shows a trend. It seems that we can know the expected maximum strength of the weld joint if we have information of the fracture toughness of steel. In the figure an empirical formula presenting the relationship between the expected strength of weld and the fracture toughness of the base metal.

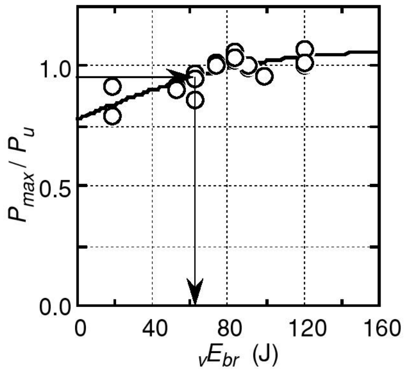


Figure 4: Relationships between joint strength and fracture toughness

In designing the welded connection, designers first evaluate the expected force acting on the weld by the structural analysis and the above-mentioned calculation. Then they can confirm their tentative connection design by comparing the expected force with the strength of the weld joint which may vary depending on the fracture toughness of the steel the designers choose for their design.

3. CONCLUDING REMARK

As a concluding remark, the connection design sequence is described below.

1) The structural analysis is carried out on the tentatively determined framework for earthquake waveforms with a design intensity.

2) The required beam-end rotation is figured out at a specified portion of the frame from the analysis output.

3) To choose a type of connection. The connection detail is recommended in this paper.

4) The flange force acting on the weld joint is calculated by the CDC method or other calculation tools. A portion

of the web of the beam should be ignored in the calculation, in case the column is the square hollow section.

5) To select a suitable steel which guarantees the enough fracture toughness, keeping the expected strength of the

weld joint for the selected steel plate greater than the calculated flange force.

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Inoue et al. (1999)," Ductility demanded of members in steel moment frames sustaining beam-hinging mechanism 1~6 ", Proceedings AIJ Annual Convention (to be published)

Bennet,P.E. and Sinclair,G.M. (1966)," Parameter Representation of Low-temperature Yield Behavior of Body-centered Cubic Transition Metals, " Transaction ASME, pp518-524.

Appendix I A typical beam-to-column connection and the recommended detail of weld joint

More than 90% of steel buildings are less than 5 story buildings. The structural configuration of these buildings is in general the resistant moment frame which is composed of square hollow section columns and H-shape beams. A typical connection in the frame is as shown in Fig.A1.1. The flange plates of the beam are welded to the edge of the through diaphragm crossing the column section. There are some details used in practice for welding the flange to the diaphragm as shown in Fig.A1.2. The details are characterized by the shape of the weld access hole and the location of weld fixing the backing bar at the right position. One of the authors conducted cyclic bending tests on the T-type beam-to-column connections which have the different types of welded joint details. The results show various behavior. Some were easily ruptured in a few cycles, but some were well deformed without premature fracture. A joint detail to be recommended is one in Fig.A1.2(b). In fact, the specimen with this type of detail shows a good structural performance as shown in Fig.A1.3. We can expect enough ductility in this connection.

Note Electrodes: YGW11 mm
YGW18 1.4mm
Heat input: 25-30kJ/cm
Inter pass temperature: less than 300^{o}C

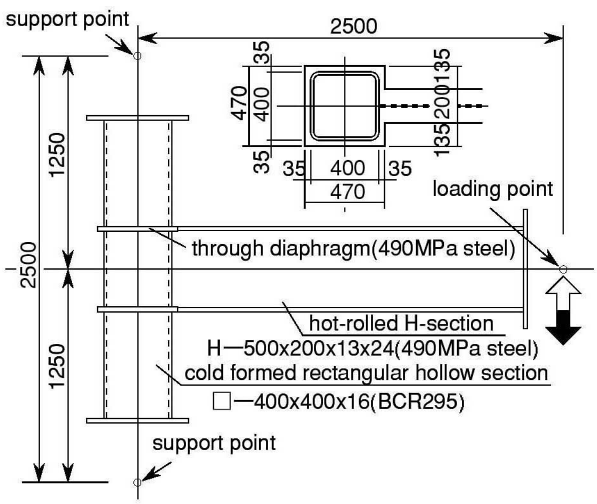
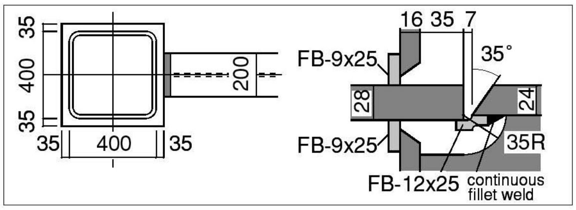
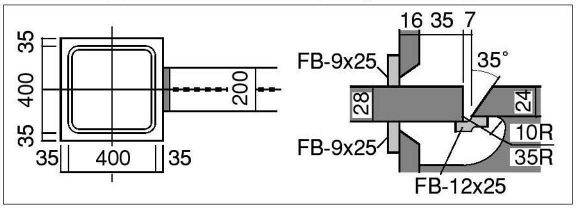


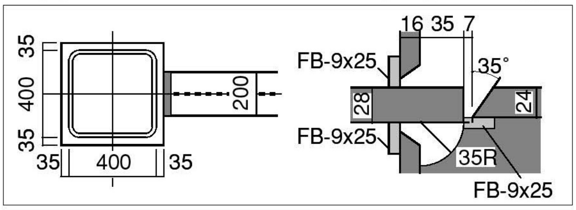
Figure A1.1: Specimen configuration and loading condition



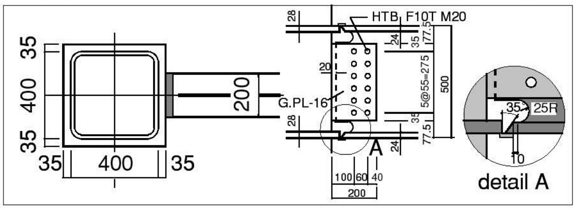
(a) Conventional(shop welding)



(b) Revised weld access hole(shop welding)



(c) Revised weld access hole(shop welding)



(d) Revised weld access hole(site welding)

Figure A1.2: Detail of joint

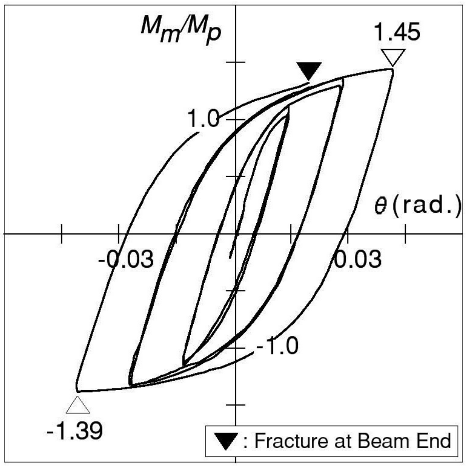


Figure A1.3: Beam end moment vs. relative rotation of beam end connection relationship

Appendix II Relationship between Flange Force and End Rotation Angle of a Beam

The Column Deflection Method (CDC method) can calculate the relationship between the flange force and the end rotation angle of a beam. A portion of the web is ignored as shown in Fig.A2.1, according to the evidence in the stress distribution of the web in the vicinity of the column surface of square hollow section. The relationship obtained as shown in Fig.A2.2 is depending also on the yield ratio YR of the steel. In the figure, the end rotation angle is denoted as bp in the horizontal axis and the flange force Pf in the vertical axis is expressed in a non-dimensional form as Pf / Pu, where Pu = u Af, u = the tensile strength, Af = the section area of a flange. The calculation result is verified by the experiments conducted by the authors.

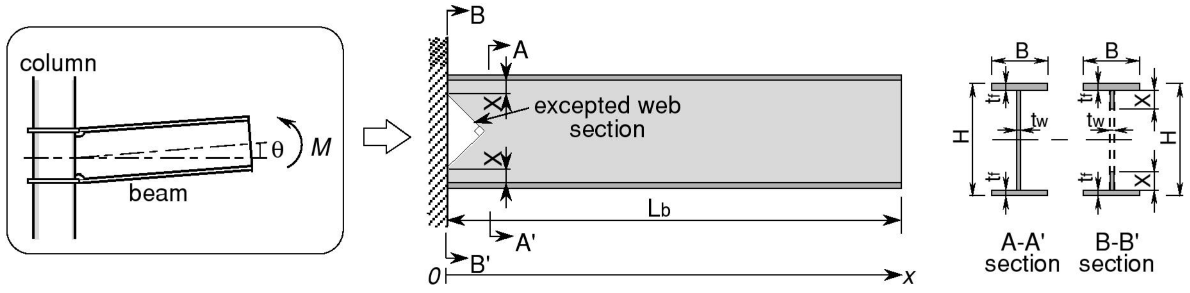


Figure A2.1: Configuration of CDC method model

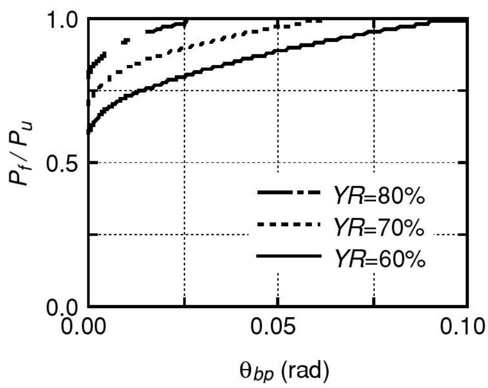


Figure A2.2: Flange force vs. plastic end rotation angle relationships

Appendix III Tension Tests on Welded Joints

The tension tests were conducted on the welded joint as shown in Fig.A3.1. The weld joint is centered in the specimen. The left part of the weld is regarded as the through diaphragm, while the right part is regarded as the flange plate. The right part is so tapered that the stress distribution is gradually changing just as the stress in the flange induced due to bending moment. A surface notch was intentionally provided at the end of weld bead as shown in Fig.A3.2. The depth of the notch varies from 3 ~ 25 mm and the length from 3 ~ 40 mm. The detail of weld joint is illustrated in Fig.A3.3, where the groove preparation of a single bevel groove weld such as the root opening and the groove angle is also shown. The weld was made by the CO2 gas shielded metal arc. Other welding conditions are shown in the figure.

The other test parameters are the quality of the steel, the loading speed and the test temperature: The specimens were made of two kinds of steels; a high toughness steel and a low toughness steel. The yield ratios of the steels differ a little. In order to examine the effect of the loading speed on fracture, the tests were conducted under the high speed loading, say, 300 mm /sec of the ram speed and the quasi-static loading. The test temperature must be a very important parameter in the fracture tests. In these tests, the temperature was carefully kept at specified temperatures, that is, 0, -20, -40 degree in the centigrade. The effect of the strain-rate and the temperature on the strength of steels can be comprehensively expressed in empirical formulas using the strain rate-temperature parameter R [Bennet and Sinlair, 1966]. Following these formulas, the strength of the steels used in the tests was uniformly evaluated. Fig.A3.4 demonstrates good coincidence in the stress-strain curves between the evaluated values and the experimental results. The tensile strength of the plate of each specimen, Pu, was calculated from the evaluated value of steel strength.

The fracture toughness was evaluated by the Charpy V-notch test and expressed as the absorption energy. The specimens for the Charpy test were taken from the vicinity of the spot from where the fracture initiated. The results of the tension tests are summarized in Fig.A3.5. The recorded ultimate strength Pmax, in the non-dimension form, Pmax / Pu, is plotted against the measured energy absorption vEbr. In spite that there were several sizes of notches in the specimens, the data are scattered in a rather narrow band. The regression formula was made and illustrated in the figure. It seems that we can guess the expected strength of weld joints, provided the fracture toughness of the steel to be used is known.

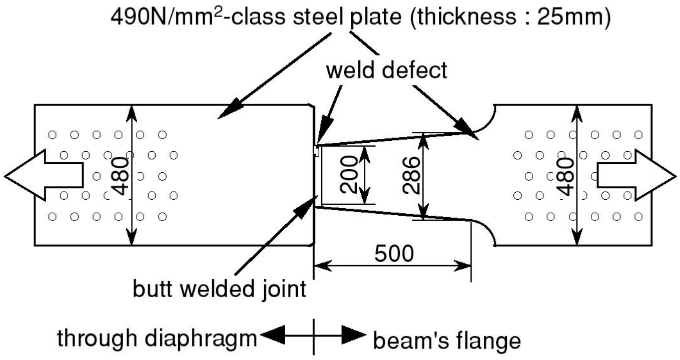
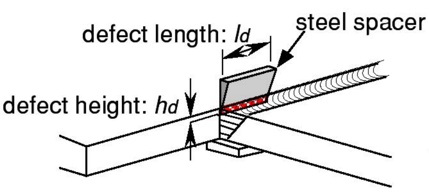
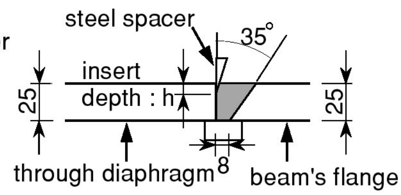


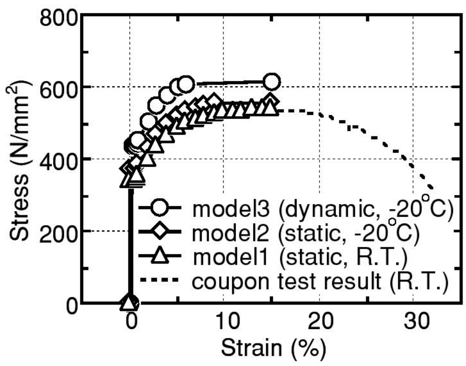
Figure A3.1: Specimen configuration of tension test





process	CO_2 welding
position	flat position
heat input	< 30kJ/cm
preheating	none
interpass temperature	< 300°C

Figure A3.2: Location of defect **Figure A3.3: Detail of joint and welding condition**



$$\frac{P_{\max}}{P_u} = 0.777 + 0.00362\,{}_vE_{br} - 0.0000117\,{}_vE_{br}^2$$

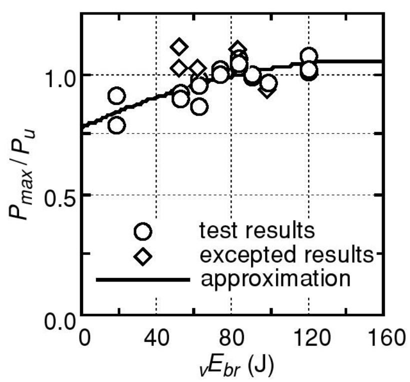


Figure A3.4: Stress-strain models **Figure A3.5: Joint strength vs. fracture toughness relationships**