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STRENGTH AND DEFORMATION CAPACITY OF STEEL BRACE UNDER HIGH-SPEED LOADING

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SUMMARY

Plastic deformations at connections or flames are important condition for earthquakeproof structure in order to prevent a whole collapse. Therefore, a connection part in a steel structure is defined to be more than 1.2 times as strong as a flame nowadays in Japan. But this definition has been concluded from only statical experiments, so that we did an actual experiment in order to investigate effects of strain velocity for safety earthquakeproof design under dynamic loading. It is understood from the experiment that the factor of safety (1.2) should be larger than current value.

INTRODUCTION

It is important problem for earthquakeproof structure to be deformed plastically in order to prevent a whole collapse of the structure subjected to a large earthquake. Braces are one of the important elements for earthquakeproof structural design in a gymnasium or a warehouse for examples. Therefore, a connection part of the brace is defined to be more than 1.2 times as strong as the brace itself. It means the connection can resist the force which full plastic moment occurs on the brace. Many experimental studies have been done in order to evaluate safety of the earthquakeproof structures, but most of them were the studies based on statical experiments (Ref. 1) so that they may be unsuitable to investigate actual behaviour of braces subject to dynamic loading under the earthquake. Furthermore, it is well known that the relationship between strees and strain is influenced by the loading velocity (Ref. 2). But this affect have not been treated quantitatively till now.

Therefore, this paper deals with a material test with dynamic loading and an experiment of actual braces with the dynamic loading in order to offer some fundamental data for evaluating the safety of earthquakeproof structures.

MATERIAL TEST WITH DYNAMIC LOADING

Outline of Test Test pieces were made from an angle or channel (SS41) used in the experiment of actual braces (the following paragraph). The configuration and it's scale are shown in Fig. 1. Chemical composition of the material is shown in Table 1 and five constant loading velocities are shown in Table 2. Optical displacement measuring device were applied in the test to measure the displacement.

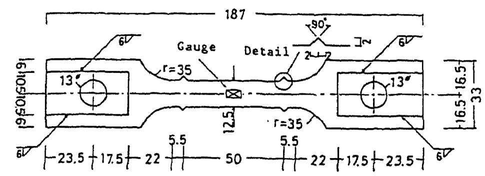

Fig. 1 Configration of Test Piece for High-Speed Tensile Test

Table. 1 Chemical Composition of Material

(%)

Test Piece	C	Si	Mn	P	S	Cu	Sn	Ni	Cr
A	0.23	0.13	0.45	0.052	0.029	0.66	0.045	0.086	0.017
B	0.13	0.15	0.54	0.028	0.033	—	—	—	—
C	0.25	0.14	0.43	0.045	0.032	0.68	0.023	0.095	0.18
D	0.26	0.13	0.42	0.034	0.025	0.39	0.025	0.085	0.18

Table. 2 Loading Velocity of Tensile Test

V1	V2	V3	V4	V5
Satic Loading	0.1cm/s	1.0cm/s	10cm/s	100cm/s

Results and Consideration of Test All result obtained from the test is shown in Table 3 and one example of the stress - strain curve is shown in Fig. 2. The values in the Table mean the average values of same kind of test pieces. Loading velocities during elastic region and plastic region are represented separately, because loading velocities changed remarkably after elastic region. It is recognized that both of yield strength and ultimate strength shift to higher as loading velocity increase, particularly upper yield strength shift to remarkably higher. It is considered that yield strength is influenced by the loading velocity of elastic region, and ultimate strength is influenced by the one of plastic region. These results are shown in Fig. 3 - Fig. 5. The curves in these figures indicate approximate curves which are obtained by using the least squares method. The approximate formulas can be represented as follows.

$$Dsyu=1.378+0.151\log_{10}\dot{e}_e+0.0151(\log_{10}\dot{e}_e)^2 \quad (1)$$
$$Dsyl=1.272+0.109\log_{10}\dot{e}_p+0.0109(\log_{10}\dot{e}_p)^2 \quad (2)$$
$$Dsu=1.080+0.040\log_{10}\dot{e}_e+0.005(\log_{10}\dot{e}_e)^2 \quad (3)$$

$$10^{-5} \leqq \dot{e}_e \leqq 3.0 \qquad 10^{-4} \leqq \dot{e}_p \leqq 17$$

where Dsyu: Increasing rate of upper yield strength
$\dot{e}_e$: Loading velocity during elastic region
Dsy: increasing rate of lower yield strength
$\dot{e}_p$: Loading velocity during plastic region
Dsu: Increasing rate of ultimate strength

Table. 3 Result of Test

	Syu (kgf/mm²)	Syl (kgf/mm²)	est (%)	Su (kgf/mm²)	δu (%)	δf (%)	Φ (%)	Yh (Syh/Su)	Yl (Syl/Su)	$\dot{e}_e$ (%/s)	$\dot{e}_p$ (%/s)
PAV5	55.4	50.2	3.96	64.3	17.3	32.2	51.0	0.862	0.780	2.9	10
PAV4	46.5	45.3	1.98	63.1	14.1	29.2	49.4	0.737	0.718	$8.3\cdot10^{-2}$	1.4
PAV3	44.1	42.5	1.92	61.4	17.0	27.6	47.4	0.717	0.691	$1.5\cdot10^{-2}$	$1.4\cdot10^{-1}$
PAV2	—	—	—	—	—	25.4	45.8	—	—	—	—
PAV1	38.9	37.5	1.18	57.4	18.9	28.9	49.9	0.677	0.652	$7.5\cdot10^{-6}$	$1.0\cdot10^{-4}$
PBV5	53.7	43.7	3.56	58.2	21.5	31.9	58.6	0.924	0.750	2.6	10
PBV4	45.0	43.6	3.04	55.1	20.5	31.3	56.9	0.817	0.792	$1.1\cdot10^{-1}$	1.4
PBV3	41.1	39.9	2.70	54.0	19.3	29.7	59.9	0.761	0.738	$1.8\cdot10^{-2}$	$1.4\cdot10^{-1}$
PBV2	39.6	38.0	2.19	53.3	19.0	27.9	58.8	0.743	0.712	$1.1\cdot10^{-3}$	$1.2\cdot10^{-2}$
PBV1	36.3	36.3	2.40	51.0	19.4	28.0	57.7	0.711	0.711	$9.5\cdot10^{-6}$	$9.0\cdot10^{-5}$
PCV5	58.0	47.5	2.59	66.0	16.7	29.6	50.5	0.878	0.720	2.9	11
PCV4	47.3	46.5	1.92	63.4	18.0	27.9	47.3	0.746	0.733	$9.4\cdot10^{-2}$	1.4
PCV3	43.6	42.0	2.07	62.2	16.6	29.1	47.6	0.702	0.676	$1.9\cdot10^{-2}$	$1.4\cdot10^{-1}$
PCV2	42.1	40.5	1.65	60.6	15.9	28.6	47.1	0.694	0.668	$1.1\cdot10^{-3}$	$1.4\cdot10^{-2}$
PCV1	38.9	38.6	1.89	59.1	18.9	28.2	49.8	0.658	0.653	$7.5\cdot10^{-6}$	$1.0\cdot10^{-4}$
PDV5	52.3	47.8	3.04	57.8	19.6	31.0	53.8	0.905	0.827	3.0	17
PDV4	42.7	41.7	2.81	56.3	19.6	29.2	52.2	0.758	0.741	$1.3\cdot10^{-1}$	1.4
PDV3	39.0	38.1	2.11	53.6	19.5	27.0	51.9	0.728	0.711	$1.2\cdot10^{-2}$	$1.4\cdot10^{-1}$
PDV2	38.2	35.5	2.07	53.4	19.3	26.0	53.2	0.716	0.665	$1.1\cdot10^{-3}$	$1.4\cdot10^{-2}$
PDV1	34.7	33.8	2.07	51.8	19.0	26.2	50.3	0.671	0.653	$7.0\cdot10^{-6}$	$1.2\cdot10^{-4}$

S_{yu}: Upper yield stress
S_{yl}: Lower yield stress
S_u: Ultimate stress
δ_u: Uniform elongation
δ_f: Strain at failure
ø: Reduction of section area
e_{st}: Strain at the beginning of strain hardening
Y_u: Ratio of upper yield stress to ultimate stress
e_p: Strain velocity during plastic deformation

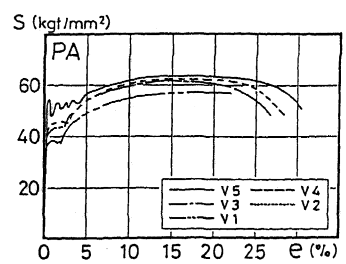

Fig. 2 Stress-Strain Curves

There is not remarkable changes about uniform elongation (δu) and elongation after fracture (δf), but it may be recognized that both of them slightly increase according to increasing the loading velocity.

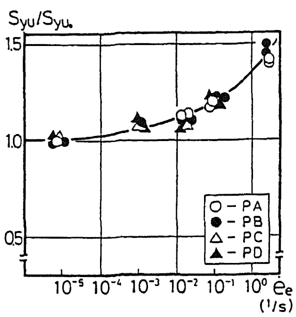

Fig. 3 Relationship Between Strain Velocity During Elastic Region and Upper Yield Stress

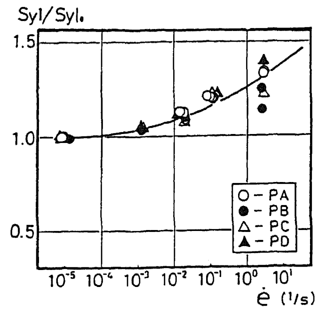

Fig. 4 Relationship Between Strain Velocity During Elastic Region and Lower Yield Stress

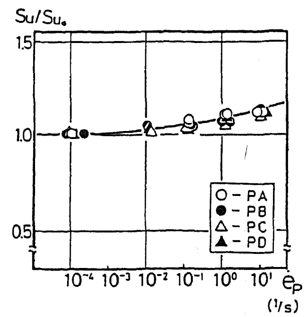

Fig. 5 Relationship Between Strain Velocity During Plastic Region and Ultimate Strength

EXPERIMENT OF ACTUAL BRACE

Outline of Experiment Three kinds of specimens, two types of L- 65x65x6 angles (LB and LC) and L- 75x75x6 angle (LA), were prepared for the experiment. Table 4 shows diameters and numbers of applied bolts. o in the figure means that the connection part can resist more than 1.2 times as the brace itself, and x means the connection part can not resist more than it. Standard bolt pitch was applied for these connection parts. The testing machine is shown in Fig. 6. 25cm/sec (H), 0.25cm/sec (M) and statical loading (L) were selected as loading velocities for the experiment.

Table. 4 List of Tested Brace and Connection

	Applied Brace	M20x2	M20x3	M16x3	M16x4	M16x5
LA	L-75x75x6	—	X	—	O	O
LB	L-65x65x6	X	—	X	—	O
2LC	L-65x65x6	—	—	—	X	O

O : Connection Part Satisfies Formula (4)
X : Connection Part does not Satisfies Formula (4)

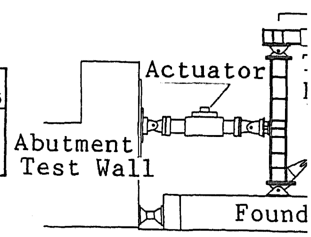

Fig. 6 Load

Results and Consideration of Experiment Table 5 shows al
the experiment. Strain velocity of the axial direction aft
represented as strain velocity (V) in the Table. Load
obtained from three different type of specimens are shown
is recognized from Fig. 7 and Fig. 8 (LA type and LB typ
area of the braces didn't yield until rupture and the el
decrease remarkably in case of only high velocity loadi
become larger according to loading velocity increases as m
paragraph. Therefore, the phenomena described above can
considered that this phenomena is very important problem

proof structural design. But braces could be deformed enough in case of 2LC (two parallel braces) so that we can apply even angle braces by using them double.

Table. 5 Result of Experiment

Applied Brace	Py (tf)	Pmax (tf)	δu (mm)	Pf (tf)	δf (mm)	Ps (tf)	V (cm/s)
LA-3M20-L-1	—	28.2	37.6	17.3	48.2	19.8	—
LA-3M20-M-1	—	28.4	34.9	19.0	39.8	17.9	0.23
LA-3M20-H-1	—	39.3	21.5	26.9	28.4	23.9	29.9
LA-3M20-H-2	—	32.4	19.4	24.3	19.4	26.4	29.7
LA-4M16-L-1	29.13	30.0	87.7	20.7	98.5	18.7	—
LA-4M16-M-1	29.50	30.6	95.0	30.6	95.0	19.3	0.22
LA-4M16-H-1	—	32.5	29.8	32.5	29.8	25.0	27.3
LA-4M16-H-1	—	32.8	30.9	32.5	31.8	26.4	40.0
LA-5M16-L-1	28.34	31.9	103.1	31.9	103.1	15.4	—
LA-5M16-M-1	29.50	31.6	99.2	31.6	99.2	23.3	0.22
LA-5M16-H-1	35.89	35.6	17.4	32.2	94.2	29.2	31.1
LA-5M16-H-2	—	32.8	16.0	32.6	23.1	29.1	43.7
LB-2M20-L-1	—	19.6	27.6	1.3	105.0	12.5	—
LB-2M20-L-2	—	19.2	32.4	0.9	116.8	10.7	—
LB-2M20-H-1	—	20.7	25.0	1.2	111.2	12.4	14.2
LB-2M20-H-2	—	19.3	23.4	0.3	116.8	12.6	9.5
LB-3M16-L-1	—	24.7	39.6	17.2	64.3	12.8	—
LB-3M16-L-2	—	23.4	36.5	14.5	58.7	13.4	—
LB-3M16-H-2	—	23.9	19.3	21.5	32.1	15.4	11.3
LB-3M16-H-3	—	26.7	7.9	19.6	45.3	18.6	32.2
LB-5M16-L-1	—	26.2	108.8	26.2	108.8	26.1	—
LB-5M16-L-2	—	26.0	103.9	21.4	110.5	19.2	—
LB-5M16-H-1	24.3	33.5	18.4	25.2	28.6	25.6	31.1
LB-5M16-H-2	24.1	31.1	20.5	25.4	31.4	25.8	31.2
2LC-4M16-L-1	50.4	55.5	99.4	55.4	102.5	47.5	—
2LC-4M16-M-1	50.8	56.2	103.5	51.8	108.0	40.7	0.24
2LC-4M16-H-1	58.7	58.7	16.8	54.3	86.2	50.8	24.0
2LC-4M16-H-2	59.7	59.7	18.4	57.0	96.8	50.5	24.7
2LC-5M16-L-1	50.7	56.5	101.6	51.7	104.2	46.8	—
2LC-5M16-M-1	51.2	56.3	93.3	51.9	93.7	45.2	0.24
2LC-5M16-H-1	59.3	59.5	103.6	59.5	103.6	50.6	22.5
2LC-5M16-H-2	58.7	58.7	8.4	56.7	95.5	57.1	21.4

Py: Yield Stress of Brace Ps: Slip Load at Connection
δu: Elongation at Maximum Load Pf: Fracture Load
δf: Desplacement at Failure Pu: Maximum Load

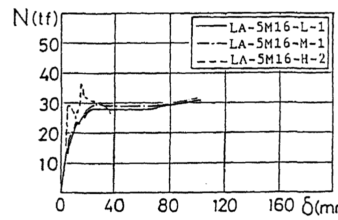

Fig. 7 Load-Displacement Curves (Comparison between Three Loading Velocities)

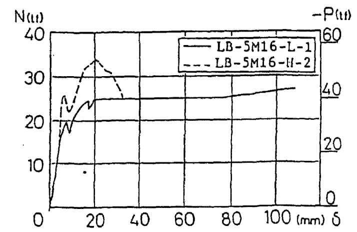

Fig. 8 Load-Displacement Curves (Comparison between Two Loading Velocities)

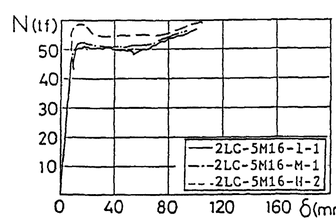

Fig. 9 Load-Displacement Curves (Comparison between Three Loading Velocities)

<u>Evaluation of Connection Part</u> It is usually defined that connection parts must be designed as following.

$$1.2\ Ag \cdot Sy \leqq Ae \cdot Su \tag{4}$$

where Ag: cross-sectional area of a brace, Sy: yield strength of the material, Ae: effective sectional area and Su: ultimate strength of the material.

This formula can be easily changed as

$$Ku = Ae \cdot Su \ /\ Ag \cdot Sy \tag{5}$$

here Ku is a coefficient for judgment of a connection part.

It can be understood that brace would yield if Ku is larger than 1, and brace can't yield if Ku is smaller than 1 from this formula. The other word, Ku value should be more than 1 for safety earthquakeproof design.

Methods for measurement of effective sectional area is one of important problems in order to design connection parts. Original calculation for it is proposed by Load and Resistance Factor Design (LRFD)(Ref. 4). Fig 11 shows a comparison between calculated ultimate strengths (effective sectional area is calculated with LRFD method) and experimental values. It is considered that this LRFD method is useful for proper design of connection parts.

Effect of strain velocity is also considered to be one of important problems. Therefore another formula is given by considering the effect as following.

$$Ku' = Ku \ / \ K \qquad (6)$$

$$K = Dsy \ / \ Dsu \qquad (7)$$

Calculated Ku' values on appropriate strain velocities are shown in Table 6 and Table 7. These Ku' values are compared with experimental values in Fig. 11 and Fig. 12. It is recognized from these figures that Ku' values calculated from lower yield stress agree well with experimental values, but we think upper yield stress should be applied to give more safety earthquakeproof design.

Furthermore, yield strength ratio under statical loading is also important factor. It has been reported that mean value of yield strength ratio is 0.695 and standard deviation of it is 0.0636 in case of SS41 steel (Ref. 3). But 0.585 is normally applied for the value on SS41 steel. The value of K become 1.13 by using formula (1),(3) and (7) with considering effects of represented strain velocities ($\dot{e}_e$=0.1/sec, $\dot{e}_p$=1.0/sec). We propose that the value of K should be more than 1.2, which is applied nowadays, by considering the effects of both strain velocity and yield strength ratio.

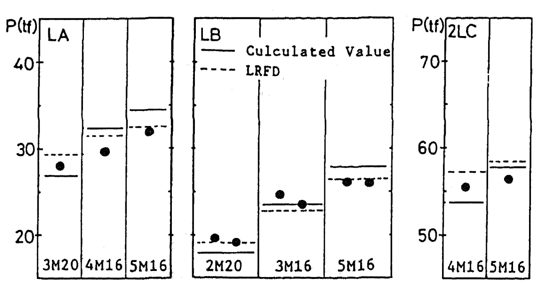

Fig. 10 Comparison of Maximum Load between Experimental Value and Culculated Value

Table. 6 List of Ku Values at High-speed Loading

Brace	Strain Velocity (sec^{-1})	σyu, σyl σu (tf/cm^2)	Yield Load at Brace P'y (tf)	Maximum Load P'max (tf)	ku(U) ku(L)
LA-3M20-L	$\dot{e}e=1.0\times10^{-5}$	σyu 3.89	Pyu 31.9	28.4	0.891 0.925
LA-4M16-L	$\dot{e}p=1.0\times10^{-4}$	σyl 3.75		31.2	0.977 1.01
LA-5M16-L		σu 5.74	Pyl 30.8	32.6	1.02 1.06
LA-3M20-M	$\dot{e}e=1.0\times10^{-3}$	σyu 4.12	Pyu 33.9	29.0	0.857 0.904
LA-4M16-M	$\dot{e}p=1.0\times10^{-2}$	σyl 3.91		31.8	0.940 0.991
LA-5M16-M		σu 5.85	Pyl 32.1	33.2	0.981 1.03
LA-3M20-H	$\dot{e}e=1.0\times10^{-1}$	σyu 4.83	Pyu 39.6	30.7	0.776 0.851
LA-4M16-H	$\dot{e}p=1.0\times10^{0}$	σyl 4.40		33.6	0.850 0.932
LA-5M16-H		σu 6.20	Pyl 36.1	35.2	0.887 0.974

Table. 7 List of Ku Values at High-speed Loading

LRFD

Brace	Strain Velocity (sec^{-1})	σyu, σyl, σu (tf/cm^2)	Yield Load at Brace $P'y$ (tf)	Maximum Load $P'max$ (tf)	$k'u$(U) / $k'u$(L)
2LC-4M16-L	$\dot{e}e=1.0\times10^{-5}$	σyu= 3.89, σyl= 3.86	Pyu 53.6	57.3	1.07 / 1.08
2LC-5M16-L	$\dot{e}p=1.0\times10^{-4}$	σu = 5.91	Pyl 53.1	58.5	1.09 / 1.10
2LC-4M16-M	$\dot{e}e=1.0\times10^{-3}$	σyu= 4.13, σyl= 4.03	Pyu 56.9	58.4	1.03 / 1.05
2LC-5M16-M	$\dot{e}p=1.0\times10^{-2}$	σu= 6.03	Pyl 55.5	59.6	1.05 / 1.07
2LC-4M16-H	$\dot{e}e=1.0\times10^{-1}$	σyu= 4.83, σyl= 4.53	Pyu 66.6	61.9	0.929 / 0.991
2LC-5M16-H	$\dot{e}p=1.0\times10^{0}$	σu = 6.38	Pyl 62.4	63.1	0.948 / 1.01

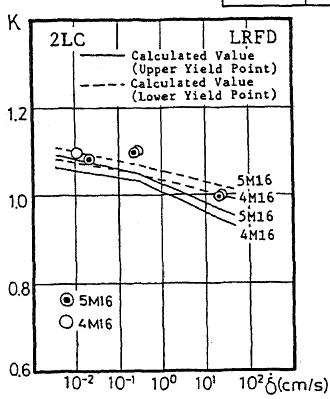

Fig. 11 Comparison between Experimental Value and Culculated Value

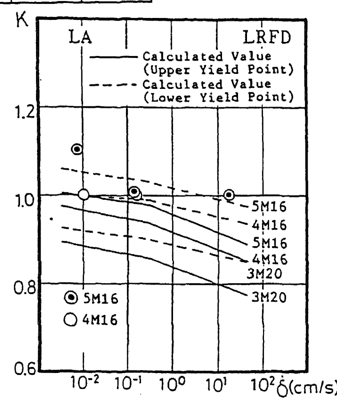

Fig. 12 Comparison between Experimental Value and Culculated Value

CONCLUSION

This paper indicates that the behaviour of steel element, which is expected to have stress concentrations, under dynamic loading can be numerically analyzed. Also K value, applied for safety earthquakeproof design of steel braces and their connections, should be changed larger than the present value.

We think it is necessary to keep on the investigation in order to obtain a certain condition of safety earthquakeproof design of steel braces and the connections.

REFERENCES

1. Y. Tanuma, B. Katou et al., "Research on the Brace Joints of Steel Angle with High Strength Bolts," Transactions of The Architectural Institute of Japan, 32-39, Mar., (1983).
2. H. Aoki, B. katou et al., "Influences of Test Temperature and Load Velocity on Ultimate Strength and Deformation of Notched Steel Elements," Transactions of The Architectural Institute of Japan, 36-44, Dec., (1982).
3. H. Aoki, K. Murata et al., "Statistical Study on Yield Point, Tensile Strength and Yield Ratio of Structural Steel," Transactions of The Architectural Institute of Japan, 167-168, Jan., (1984).
4. Architectural Institute of Japan, Load and Resistance Factor Design for Steel Structures (Proposal), Mar., (1986)