An Experimental Study on the Axial Collapse Characteristics of Hat and Double Hat Shaped Section Members at Various Velocities

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In this study, the axial collapse tests were performed under either static (or quasi-static) or impact loads with several collapse velocities based on the expectation that para-closed sections of the front-end side members (spot welded hat and double hat shaped section members) would show quite different collapse characteristics from those for seamless section. The test results showed that both of the hat and double hat shaped section members failed in the stable sequential collapse mode in the static or quasi-static collapse tests, while the double hat shaped section members underwent the unstable collapse mode especially when the impact velocity is high. The mean collapse loads in the hat shaped section members increase with collapse velocity for all the cases of the static, quasi-static, and impact collapse tests. In the double hat shaped section members, however, the mean collapse loads decrease with increase in collapse velocity in the impact tests.

Key Words : Hat and Double Hat Shaped Section Members, Spot Welded, Axial Collapse, Collapse Characteristics, Mean Collapse Load

1. Introduction

With a tendency toward rapid transit, the collapse safety efficiency of vehicle members has increasingly been focused at the same time. The collapse safety efficiency is the capability to protect passengers in a car accident, and is decided by the conditions of the collision, structural integrity and passenger protecting equipment, etc. The front-end collisions including inclined collisions occur more frequently than side or rear collisions, thus the safety efficiency of the front-end collisions has been very important issue in the vehicle development (Ishikawa, 1985 ; Syamal et al., 1995). Since the impact energy inflicts a fatal injury upon passengers especially during initial collision, the front-end members of vehicles must absorb the impact energy effectively to ensure passenger's safety in front-end collisions.

The front-end section members of vehicles have been designed to absorb the impact energy through plastic deformation during front-end collision. These section members are mostly hat shaped and are spot welded. Studies on the collapse characteristics of these section members, however, were focused on the collapse characteristics for various seamless section members which have a closed loop cross section (Li et al., 1990 ; Krauss et al., 1994 : Avalle et al., 1997 ;

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Singace, 1999 ; Bardi et al., 2003 ; Han et al., 1998a, 1998b, ; Kim et al., 1997). In recent years, numerous experiments and finite element works are under way to investigate the collapse characteristics for members with spot welded hat shaped section which is nearer to the actual section than the simplified seamless section (White et al., 1999a, 1999b ; Cha et al., 2001, 2002 ; Lee et al., 2002). These cross sections are not closed except the area of the spot welded, which makes it difficult to analyze the collapse characteristics of these section members.

In this study, the axial compression tests were carried out for members having either spot welded hat or double hat shaped section. The members have various spot weld pitches in flange. The collapse velocities are varied as test modes : static (0.00017 m/sec), quasi-static (0.017 m/sec) and impact tests (4.7, 6.5, 6.8, 7.2, 7.3 m/sec). Several collapse characteristics, such as collapse modes, maximum collapse load and mean collapse load were analyzed from the test for the two kinds of specimens, and the results were compared. For both cases of spot welded hat and double hat shaped section members, the collapse characteristics were turned out to be influenced by the size of spot welded pitch. As in the case of the seamless section members, the maximum collapse load and mean collapse load increased with increase in collapse velocity in the (single) hat shaped section members. In the double hat shaped section members, however, the mean collapse loads increase with increase in collapse velocity in the static and quasi-static tests, while the mean collapse loads decrease with increase in collapse velocity in the impact tests.

2. Specimens

The size of front-end section members in an actual vehicle is thickness of 1.2~1.8 mm, width ratio (breath×length) of (100~140) × (50~100) mm, length of 500~700 mm. The specimens in this study have a configuration as shown in Fig. 1, and are named as (single) hat shaped and double hat shaped section members, respectively. They were fabricated by welding two parts using
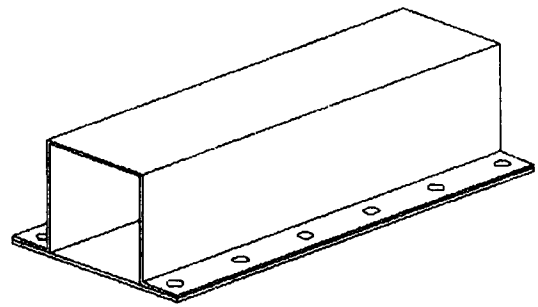
(a) Hat shaped member
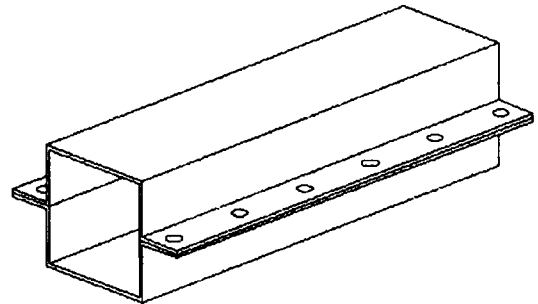
(b) Double hat shaped member

Fig. 1 Configuration of specimens

cold rolled sheet, SCP1.

The specimen used in the study has thickness of 0.78 mm, width ratio (breath×length) of 30× 30 mm, width of flange of 12 mm. The specimen size is about 1/4 of the actual vehicle front-end section members owing to the limit of impact energy of a vertical crushing testing machine used in the study. Despite the size difference between the actual vehicle section members and the specimens used in the study, the collapse characteristics change with variation of shaped section (hat and double hat shaped section members), with variation of the spot weld pitches in flange may be a guide to design a member with high energy absorbing capacity. Similar researches have been carried out for various materials and dimensions of the vehicle front-end section members (Li et al., 1990 ; Krauss et al., 1994 ; Avalle et al., 1997 ; Singace, 1999 ; White et al., 1999a, 1999b ; Cha et al., 2001, 2002 ; Lee et al., 2002 ; Bardi et al., 2003).

A theory about the folding width in the case of spot welded section members does not exist, therefore the folding theory about the seamless

section members was applied. Considering the theoretical folding width (Mahmood et al., 1981) of 22 mm in the seamless case, three types of spot weld pitch were chosen as 18.3 mm, 22 mm and 27.5 mm. The spot welding points with diameter of 6 mm are located symmetrically in the upper and lower parts. All the specimen have the specimen length of 120 mm, and the cross sectional surface area of all the specimens is the same.

Table 1 shows the mechanical properties of the material used for specimens, and the specimen designation scheme is given in Table 2. Following the scheme in Table 2, the first letter H, or D stands for hat shaped or double hat shaped, and the second letters E, F, G represent spot weld pitch. After the two letters is V_0, V_1, $\cdots$, V_6, signifying the magnitude of collapse velocity, with V_0 and V_1 standing for the static and quasi-static, respectively, and V_2, V_3, $\cdots$, V_6 for the corresponding velocities in impact tests. To illustrate, DEV3 means double hat-shaped member

Table 1 Mechanical properties of the material used for specimens

Yield strength [MPa]	Tensile strength [MPa]	Young's modulus [GPa]	Poisson's ratio	Elongation [%]
166.7	308.4	203	0.31	46.4

Table 2 Notation of the specimens

H(D)	E(F, G)	V_n	
			Type
			H : Hat shaped
			D : Double hat shaped
			Spot weld pitch
			E : 18.3 mm
			F : 22.0 mm
			G : 27.5 mm
			Collapse Velocities
			n=0 : 0.00017 m/sec
			n=1 : 0.017 m/sec
			n=2 : 4.7 m/sec
			n=3 : 6.5 m/sec
			n=4 : 6.8 m/sec
			n=5 : 7.2 m/sec
			n=6 : 7.3 m/sec

with spot weld pitch of 18.3 mm, compressed in a collapse velocity of 6.5 m/sec.

3. Collapse Test

3.1 Static and quasi-static collapse tests

The static (0.00017 m/sec) and quasi-static (0.017 m/sec) axial collapse tests were conducted by using UTM (Universal Testing Machine). The specimens were compressed until 70 mm, namely, 58.3% of the total length 120 mm by the deformation control.

As seen in Fig. 2. all the absorbed energy is equal to the area below the load-displacement curves, and is calculated by integrating the load with respect to the displacement with equation (1). The mean collapse load is obtained by dividing the absorbed energy by the collapsed length.

$$E_a = \int_{S_0}^{S} P \, dS$$
$$P_{mean} = \frac{E_a}{S} \tag{1}$$

where E_a is the absorbed energy, P_{mean} is the mean collapse load, P is the collapse load, and S is the collapsed length. Fig. 2 is the load-displacement diagrams of section members with a spot welded flange pitch of 18.3 mm which were acquired from the static collapse experiment (V_0). The solid line is for the double hat shaped
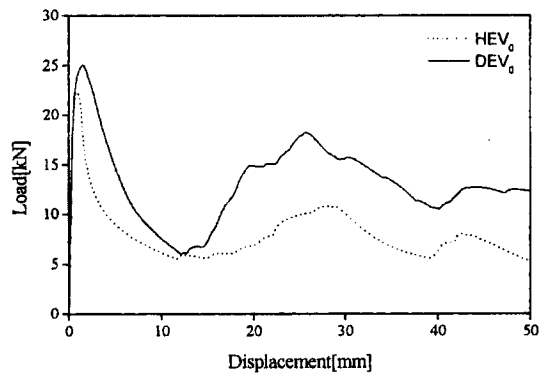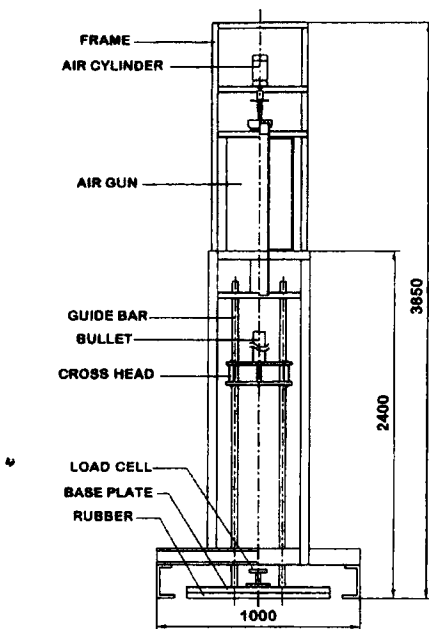

Fig. 2 Load and displacement curve of HEV_0 and DEV_0

section member and the broken line is for the hat shaped section member.

3.2 Impact collapse tests

The axial impact collapse tests were carried out by using the vertical air-compressed crushing testing machine presented in Fig. 3. The cross head is accelerated by the compressed air moved vertically along to the guide bars and inflicted the impact load on the specimens placed on the load cell. The cross head weighs 40 kilogram. Two strain gages are symmetrically placed on both sides of the load cell, and the impact loads were decided by converting the electrical resistance variations on strain gage into loads. Displacement is measured by converting the obtained voltage into displacements, where the voltage was obtained by using an Optical Deformation System (ZIMMER OHG Co. 100F) which captures the movement of target attached on the cross head. A load-displacement curve in Figs. 4 and 5 was obtained by eliminating the time axis from each measured time-load and time-displacement curves.

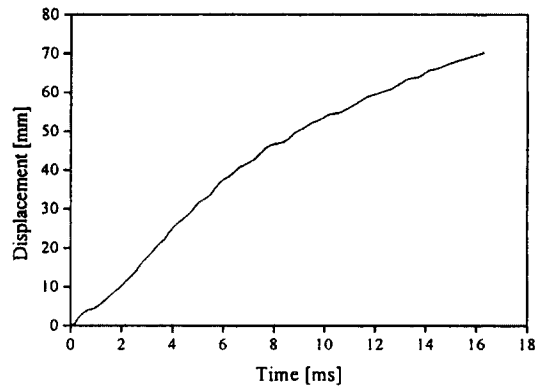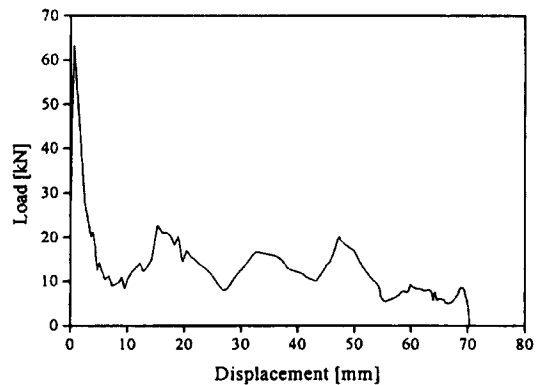Figure 4 shows the load-displacement diagram

of hat shaped section members with the spot welded flange pitch of 18.3 mm which was acquired from the impact collapse test at the impact velocities of 7.19 m/sec (V_5). Fig. 5 is that of double hat shaped section members.
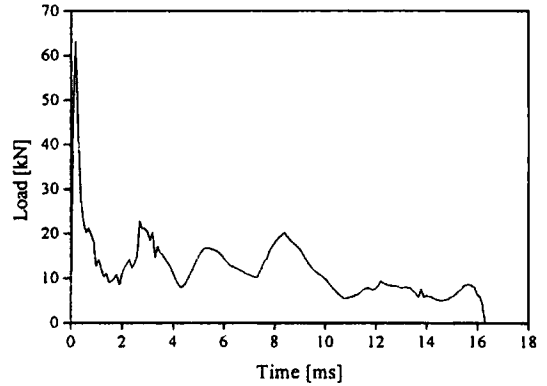
(a) Load history

(b) Displacement history

(c) Load-displacement curve

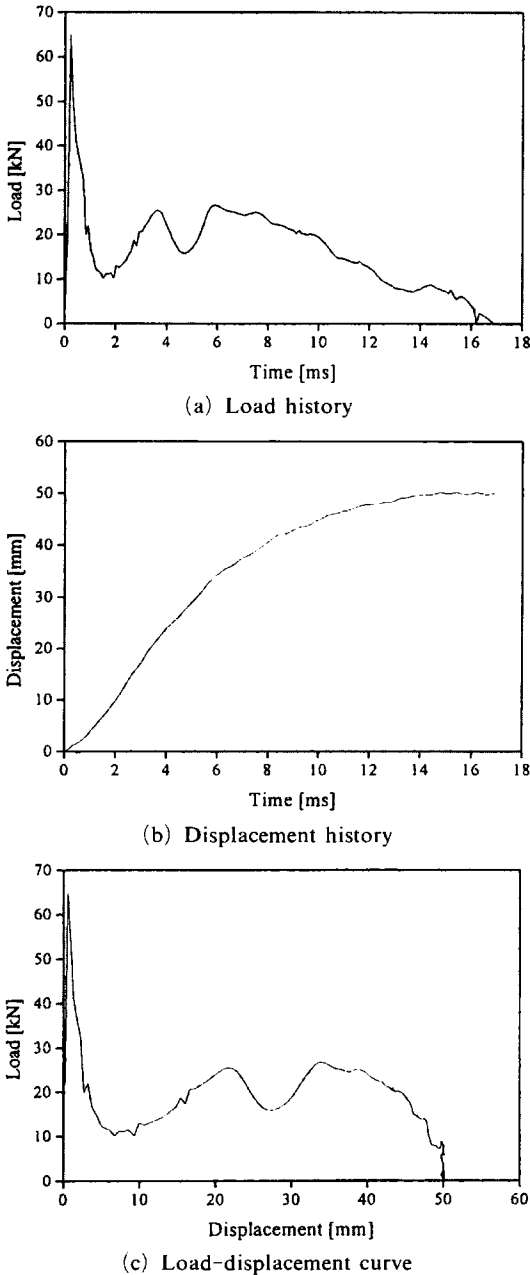**Fig. 4** Load and displacement curve of hat shaped member (HEV_5)

Fig. 3 The vertical crushing testing machine

(a) Load history

(b) Displacement history

(c) Load-displacement curve

Fig. 5 Load and displacement curve of double hat shaped member (DEV₅)

(a) HEV5

(b) DEV5

Fig. 6 Shape of collapsed specimens

4. Results and Discussion

Figure 6 presents collapsed specimens after the impact collapse tests for the specimens used in Figs. 4 and 5. In the static or quasi-static collapse tests, both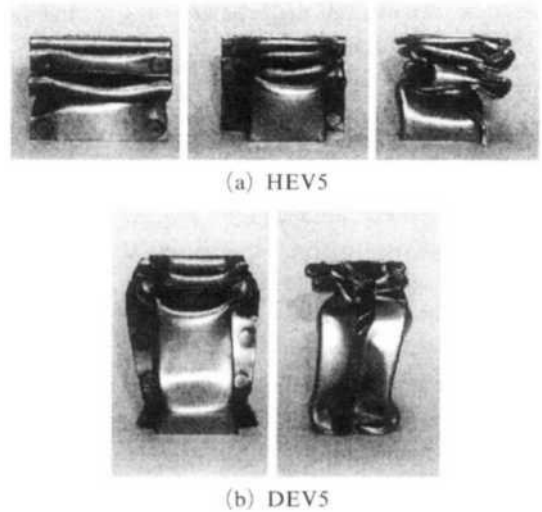 of the hat and double hat shaped section members failed in the stable sequential collapse mode. But in the impact tests, the hat shaped section members failed in the stable collapse mode, while the double hat shaped section members underwent the unstable collapse mode especially when the load velocity is high.

Tables 3 and 4 show the absorbed energy (E_a) and deformed length (S), respectively, in the hat and double hat shaped section members, with a variation of the spot welded pitches in flange and of collapse velocity. Table 5 shows mean collapse load (P_{mean}) together with the maximum collapse load $(P_{max.})$ in the hat and double hat shaped section members. In tables 3, 4 and 5, the data were the average of three or four times tests in the static and quasi-static axial collapse tests, while that of six or seven times in the impact axial collapse tests. Note here that it is the displacement control in the static and quasi-static collapse test, while the kinetic energy which will eventually be turned into the impact energy is given as an input in the impact collapse test. Therefore the mean collapse load, the absorbed energy per unit collapsed length, rather than a total of the absorbed energy is used as a basic parameter to judge an energy absorbing capacity.

Figure 7 shows a variation of the mean collapse loads in the hat and double hat shaped section members with several spot welded pitches, as a

function of collapse velocity. As spot weld pitches in the flanges are narrower, the mean collapse loads under each velocity increase considerably in hat and double hat shaped section members as shown in Table 5 and Fig. 7. During a collision process, unlike in the seamless section members, the size of folding length (collapse length) appears to strongly depend on weld pitches, and becomes smaller as the welding pitches become narrower in the spot welded section members. Therefore, section members with shorter spot weld pitches show higher absorbed energy than those with longer pitches, because the stiffness is larger for shorter folding length.

Table 3 Absorbed energy as functions of flange spot weld pitches and collapse velocities (unit : J)

weld pitch[mm] velocity[m/sec]	Hat shaped			Double hat shaped		
	18.3	22.0	27.5	18.3	22.0	27.5
0.00017	561.9	526.5	515.6	857.7	828.3	802.7
0.017	697.9	673.0	650.2	1008.7	979.0	864.8
4.7	438.5	434.5	424.1	*	*	*
6.5	826.2	826.5	824.5	831.0	833.2	822.0
6.8	903.2	902.5	903.1	903.8	900.6	901.7
7.2	1007.1	995.4	994.4	984.7	1004.8	984.6
7.3	**	**	**	1029.8	1026.6	1020.6

* : Specimens do not deform enough under this energy level
** : Specimens deform excessively beyond this energy level

Table 4 Deformed length as functions of flange spot weld pitches and collapse velocities (unit : mm)

weld pitch[mm] velocity[m/sec]	Hat shaped			Double hat shaped		
	18.3	22.0	27.5	18.3	22.0	27.5
0.00017	70	70	70	70	70	70
0.017	70	70	70	70	70	70
4.7	40	43	44	*	*	*
6.5	68	69	78	42	45	51
6.8	71	74	79	46	49	57
7.2	72	76	78	51	54	63
7.3	**	**	**	57	59	69

Table 5 Mean collapse load together with maximum collapse load (in the parenthesis) as functions of flange spot weld pitches and collapse velocities (unit : kN)

weld pitch[mm] velocity[m/sec]	Hat shaped			Double hat shaped		
	18.3	22.0	27.5	18.3	22.0	27.5
0.00017	8.0(22.7)	7.5(21.0)	7.4(19.2)	12.2(25.0)	11.8(24.2)	11.5(23.8)
0.017	10.0(32.9)	9.7(32.5)	9.3(30.6)	14.4(33.8)	14.0(33.8)	12.4(33.1)
4.7	11.0(59.3)	10.1(60.2)	9.6(58.6)	*	*	*
6.5	12.2(61.0)	12.0(60.3)	10.6(61.4)	19.8(62.3)	18.5(62.4)	16.1(63.2)
6.8	12.7(61.8)	12.2(62.4)	11.4(61.2)	19.6(65.1)	18.4(63.7)	15.8(64.4)
7.2	14.0(64.8)	13.1(61.9)	12.7(62.5)	19.3(66.1)	18.6(68.1)	15.6(62.8)
7.3	**	**	**	18.1(69.7)	17.4(71.7)	14.8(70.3)

(a) Hat shaped members
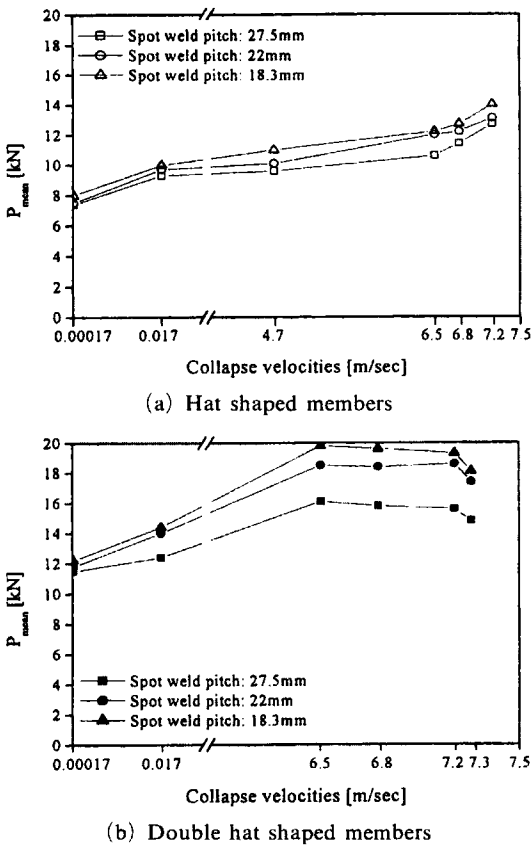

(b) Double hat shaped members

Fig. 7 Variation of the mean collapse load with collapse velocity

The amount of increase in mean collapse loads with decrease in weld pitches appeared higher in double hat shaped section members than in hat shaped section members as shown in Fig. 7. In the hat shaped section members the welding line is some distance away from the center-line of the load application point, and the bucking in the plane section members leads the collapse, thus results in the stable sequential collapse mode. In the double hat shaped section members, however, the welding line is located directly under the centerline of load application point and the buckling strength of flange which will eventually affect the collapse load increases significantly with decrease in welded pitch, because the initial folding length strongly depends on the weld pitch. An unstable collapse mode is dominant in the double hat shaped members under impact collapse, which

also supports the above mentioned idea. As a result, the mean collapse load is more influenced by the weld pitches in the double hat shaped section members than in the hat shaped section members.

The mean collapse loads increase with increase in collapse velocity in the hat shaped section members, as in the same way of seamless section members, for all the cases of the static, quasi-static, and impact collapse tests. In the double hat shaped section members, however, the mean collapse loads increase with increase in collapse velocity in the static and quasi-static tests, while the mean collapse loads decrease with increase in collapse velocity in the impact tests. In the hat shaped section members, the progressive folding mode occur during the collapse procedure, as mentioned above. The amount of absorbed energy depends on the amount of plastic deformation of the folded members, and the mean collapse load is higher for larger deformation undergoing the phenomenon of material deformation hardening. But in the case of the double hat shaped section members, the spot weld section members sustain a strong support because the welding line is directly under the load application point. This gives an initial stiffener against buckling, but does not provide additional resistance once the weld section fails, and the collapse mode is not sequential especially under high impact loads. As a result, the double hat shaped section members showed a higher mean collapse load for all the collapse velocities than the hat shaped section members, but the gap of the mean collapse loads between the two cases decrease as the collapse velocity increases. This results suggest that it is helpful in increasing the mean collapse load by making a strong stiffener under the impact load, but it is more important to induce the sequential collapse mode for high energy absorption capacities.

Figure 8 shows a variation of the maximum collapse loads in the hat and double hat shaped section members with several spot welded pitches, as a function of collapse velocity. Unlike in the mean collapse load, the effect of spot weld pitch on the maximum collapse load appears minor.
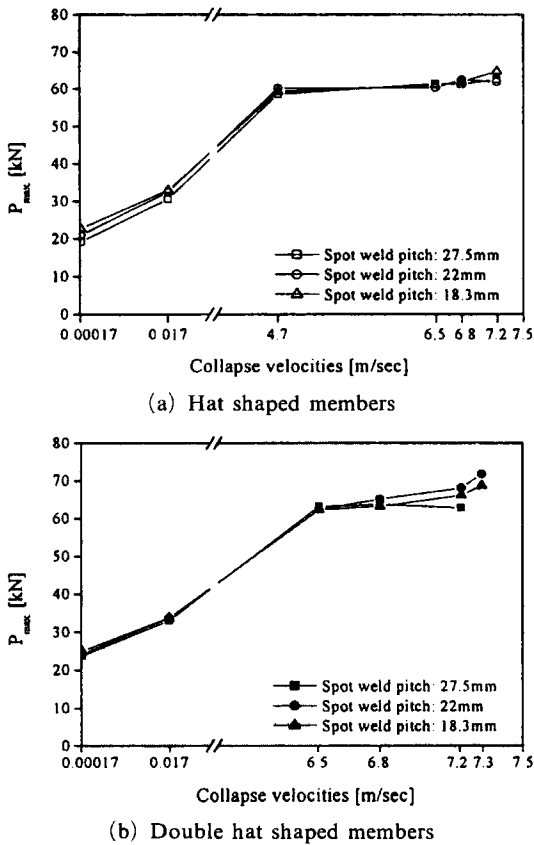
(a) Hat shaped members

(b) Double hat shaped members

Fig. 8 Variation of the maximum collapse load with collapse velocity

The maximum collapse loads increase with increase in collapse velocity both in the hat shaped section members and double hat shaped section members showing the similar trend as the mean collapse loads, though the gap of the maximum collapse loads between the hat shaped section members and double section members is smaller than that of the mean collapse loads.

5. Conclusions

The axial collapse tests were carried out on the spot welded hat and double hat shaped section members with various spot welded pitches in flange. The tests were under either static (or quasi-static) or impact loads with several collapse velocities, and the following conclusions are drawn :

(1) In the static or quasi-static collapse tests, both of the hat and double hat shaped section members failed in the stable sequential collapse mode. But in the impact tests, the hat shaped section members failed in the stable collapse mode, while the double hat shaped section members underwent the unstable collapse mode especially when the impact load velocity is high.

(2) As spot weld pitches in the flanges are narrower, the mean collapse loads under each velocity increase considerably in hat and double hat shaped section members. The amount of increase in mean collapse loads with decrease in weld pitches appeared higher in double hat shaped section members than in hat shaped section members.

(3) The mean collapse loads increase with collapse velocity in the hat shaped section members, for all the cases of the static, quasi-static, and impact collapse tests. In the double hat shaped section members, however, the mean collapse loads increase with increase in collapse velocity in the static and quasi-static tests, while the mean collapse loads decrease with increase in collapse velocity in the impact tests.

(4) The double hat shaped section members showed a higher mean collapse load for all the collapse velocities than the hat shaped section members, but the gap of the mean collapse loads between the two cases decrease as the collapse velocity increases.

Acknowledgment

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