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The Prediction of Strength of Hybrid Beams by Equivalent Section Concept

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Abstract: It is known that the application of higher strength steels to structures often results in significant material-cost savings, this research is concentrated on a study of the structural strength of hybrid flexural members using different sheet steels. A total of 72 cold-formed steel hybrid beams were investigated in this study. Since the yield strengths and stress-strain relationships of the two materials used to fabricate the beam specimens are different, the yield strength of hybrid beam can not be easily calculated. Therefore, by using the available test data, the alternative computing procedure with equivalent section concept was developed and utilized in the calculation of load-carrying capacity for cold-formed steel hybrid beam. In the determination of the strength of hybrid sections, the effective cross-sectional area calculated on the basis of the dynamic yield stresses can also be employed.

Keywords: cold-formed steel; hybrid beam; yield moment; strain rate; equivalent section; effective width.

1. Introduction

Because the member strength is influenced by impact loading, a large number of research projects were conducted for a variety of structural members under specified loading conditions during past three decades. It was found that theoretical analysis agrees well with the experimental results when taking the steel strain rate sensitivity into account for beams (Bonder and Symonds [1]; Rawlings [2]; Aspden and Cambell [3]; and Forrestal and Wesenberg [4]).

Ronald Frost and Charles Schilling [5] studied the behavior of hybrid beams consisting of higher-strength steel flanges connected with lower-strength steel webs, under pure bending and combined shear and bending. They suggested that the maximum bending strength of a hybrid beam may be considered to be (1) the moment causing the cross section to become fully plastic or (2) the moment causing initial yielding in the flange, because it has been demonstrated that the yielding which occurs in the webs of hybrid beams has little effect on the behavior of such beams.

In cold-formed steel design, local buckling is one of the major design features because of the use of large width-to-thickness ratios for compression element. For the purpose of determining the load-carrying capacity of structural components, the effective width approach has been used. The design criteria for effective design width included in the current AISI Specification [6] are primarily based on the results of static tests of cold-formed steel

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members corresponding to a strain rate approximately 1.7x10^{-6} mm/mm/sec. Pan and Yu [7,8] studied the validity of these effective design width formulas for the design of cold-formed steel members subjected to dynamic loads. It was found that the effective cross-sectional area determined according to the AISI Specification [6] can also be employed in the calculation of structural strength of cold-formed steel columns and beams under impact loads. And better predictions for load-carrying capacity can be achieved by using dynamic yield stresses or a dynamic stress-strain relationship for the specimens.

Pan and Yu [7,8] conclude that the available effective design formulas using dynamic material properties can be adequately used for the design of hybrid structural members fabricated from two different materials subjected to dynamic loads. In additions, the calculating procedure was developed in the determination of structural strength of hybrid beams and can provide a reasonable approach for calculating the critical local buckling moment, the yield moment, and the ultimate moment. However, due to the complexity for the calculation of ultimate moment using inelastic reserve capacity and the possible excessive deflection, it is suggested that for the practical design, the yield moment can be used for the load-carrying capacity of hybrid beams. In this paper, an alternative computing procedure with equivalent section concept was developed and utilized in the calculation of load-carrying capacity of cold-formed steel hybrid beams.

2. Beam specimens

The materials used in this investigation were 25AK and 50SK sheet steels with nominal yield strengths equal to approximately 172 and 345 MPa (25 and 50 ksi), respectively. These two materials have been tested for establishing the mechanical properties in tension and compression in the longitudinal and transverse directions under different strain rates of 10^{-4}, 10^{-2}, 10^{-1}, and 1.0 mm/mm/sec. Table 1 summarizes the average values of mechanical properties tested under different strain rates for 25AK and 50SK sheet steels. For details of material tests, refer to Pan, Wu, and Yu [9].

Table 1. Average mechanical properties of 25AK, 35XF, 50XF, 50SK and 100XF sheet steels under different strain rates

Strain rate (1/sec) (1)	$(F_y)_c$ (MPa) (2)	$(F_{pr})_c$ (MPa) (3)	$(F_y)_t$ (MPa) (4)	$(F_u)_t$ (MPa) (5)
(25AK sheet steel)				
0.0001	149.35	109.84	169.62	294.83
0.01	170.79	134.80	192.09	306.41
0.1	205.47	157.27	218.71	326.48
1.0	262.98	---	242.22	353.37
(50SK sheet steel)				
0.0001	367.85	289.45	379.02	462.45
0.01	385.50	292.76	391.84	475.62
0.1	392.74	305.86	400.32	489.82
1.0	409.63	---	418.73	527.47

The nominal thickness of sheet steels used for beams were 2.0 mm (0.078 in.) for 25AK sheet steel and 1.9 mm (0.074 in.) for 50SK sheet steel. All specimens were cold formed by a press-brake operation with a nominal inside-bend radius of 4.0 mm (5/32 in.). A total of 72 hat-shaped beams were tested to study the effect of strain rate on the local buckling and post-buckling strengths of compression elements. Three selected strain rates (10^{-4}, 10^{-3}, and 10^{-2} mm/mm/sec) were used in the beam tests.

As shown in Figure 1, a hat section and a plate were assembled by attaching the plate to the unstiffened flanges of the hat section to form a hat-shaped beam. Spot welds of one-inch spacing were used on each ustiffened flange of hat sections for all beams regardless the lengths of specimens. Four groups of test specimens were used in this investigation as shown in Figure 2.

- Group W - hat-shaped beams which were assembled by using a hat section fabricated from 25AK sheet steel and a plate of 50SK sheet steel. The stiffened flange of the hat section was in compression.
- Group Z - hat-shaped beams which were assembled by using a hat section fabricated from 25AK sheet steel and a plate of 50SK sheet steel. The stiffened flange of the hat section was in tension.
- Group S - hat-shaped beams which were assembled by using a hat section fabricated from 50SK sheet steel and a plate of 25AK sheet steel. The stiffened flange of the hat section was in compression.
- Group K - hat-shaped beams which were assembled by using a hat section fabricated from 50SK sheet steel and a plate of 25AK sheet steel. The stiffened flange of the hat section was in tension.

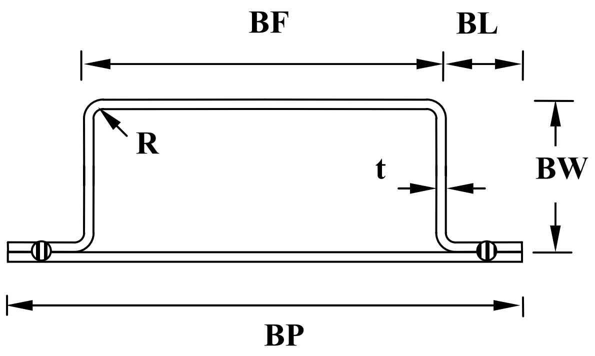

Figure 1. Cross sections of beams fabricated from 25AK and 50SK sheet steels

Three different cross sections (cases) were tested in each group. Cases A, B, and C represent the specimens with small, medium, and relatively large w/t ratio of compression element, respectively. For the specimens with the stiffened flange of hat sections on the compression side, the w/t ratios of stiffened flanges ranged from 9.26 to 63.33 and from 24.78 to 69.69 for Group W and Group S, respectively. For the specimens with the plate on the compression side, the w/t ratios of plates ranged from 25.61 to 82.49 and from 37.09 to 79.46 for Group Z and Group K, respectively. he nominal dimensions and lengths for beam specimens are listed in Table 2. Details of the dimensions and lengths for each beam specimens are presented in Pan and Yu [10].

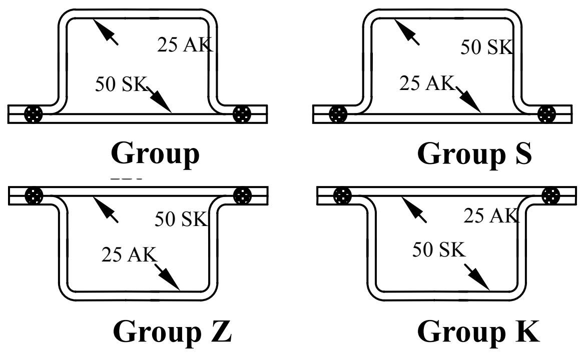

Figure 2. Configuration of beam specimens

3. Yield strength

All beam specimens were subjected to pure moments between two loading points located at one-fourth of span length from end supports. The weight of test beam specimen and the cross beam placed on the top of the specimen are light enough (approximate 80 lbs.) to be neglected in the evaluation of test results. In some lever, it is necessary to consider the effect of the weight of test specimen and cross beam in the evaluation due to the initial loading and deflection. The dynamic tensile and compressive yield stresses obtained from material tests were used for calculating the yield moment (M_y).

A total of 72 hat-shaped hybrid beams, fabricated from 25AK and 50SK sheet steels were tested under different strain rates to study the behavior of stiffened compression elements. Pan and Yu [11] concluded that the predicted critical local buckling moment, yield moment, and ultimate moment of hybrid beams can be improved by using dynamic yield stresses. Since the yield strength and stress-strain relationship of the two materials used to fabricate the beam specimens are different, the yield moment of hybrid beams can not be easily computed. Therefore, this study is concentrated on the development of an alternative procedure by using equivalent sections, which may be utilized in the calculation of load-carrying capacity of cold-formed steel hybrid beams.

Table 2. Nominal dimensions of beam specimens

Group	Case	BF (mm)	BW (mm)	BL (mm)	BP (mm)	Length (cm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
W	A	30.53	27.56	22.83	71.02	88.9
	B	68.71	39.80	22.99	109.3	152.4
	C	137.3	52.30	23.06	177.9	182.9
Z	A	30.40	27.66	22.99	71.12	88.9
	B	68.55	40.13	23.06	109.2	152.4
	C	137.2	52.37	23.04	177.8	182.9
S	A	58.45	26.54	20.19	94.11	127.0
	B	90.4	39.29	20.42	127.1	165.1
	C	142.4	51.87	20.50	177.9	182.9
K	A	58.37	26.95	20.24	93.98	127.0
	B	91.21	39.17	20.37	126.9	165.1
	C	142.3	51.97	20.50	177.8	182.9

Note: (1) For definition of symbols, see Figure 1
(2) Nominal inside radius, R=4.0 mm
(3) A total of 72 specimens were conducted in the test program (6 in each case)

3.1. Conventional method using effective design width formulas

According to the AISI Specification (1996), two procedures can be used to calculate the section strength of beams. One is based on the initiation of yielding using the effective section and the other is based on the inelastic reserve capacity. In this paper, it is assumed that the beam reaches its yield moment when the maximum edge stress in the extreme fiber reaches the yield stress of steel. In addition, the compression elements of thin-walled structural members with relatively large w/t ratios can continue to carry additional loads after the attainment of elastic buckling. However, the stresses in the compression elements will redistribute to develop the postbuckling strength. Therefore, the concept of the effective width design can be used to calculate the effective section properties. According to the AISI Specification [6], the effective design width of compression elements can be used for determining the load-carrying capacity of the member when the slenderness factor λ computed according to Eq. (1) exceeds a value of 0.673.

$$\lambda = 1.052\left[\frac{w}{t}\right]\frac{\sqrt{\frac{f}{E}}}{\sqrt{k}} \tag{1}$$

where f = stress in the element
E = modulus of elasticity of the steel, 203 kN/mm^2 (29500 ksi)
k = buckling coefficient for the flat plate
w = flat width of the element
t = thickness of the element

when λ = 0.673, the limiting width-to thickness ratio (at which full capacity is achievable) can be evaluated as for fully stiffened compression elements under a uniform stress, k = 4, which gives a limiting w/t value as follows:

$$\left[\frac{w}{t}\right]_{\lim} = 0.64\sqrt{\frac{kE}{f}} \tag{2}$$

$$\left[\frac{w}{t}\right]_{\lim} = S = 1.28\sqrt{\frac{E}{f}} \tag{3}$$

For w/t exceeding the values of S, the effective width, b, is less than the actual width w. For the purpose of calculating sectional properties, the effective width is divided into two parts and each half is positioned adjacent to each longitudinal support. Thus the width, w-b, is considered to be removed at the center of the flat width when evaluating the sectional properties. The effective width b can be calculated from the 1996 AISI Specification [6] as given in Eq. (4):

$$b = w\left[\frac{1-\frac{0.22}{\lambda}}{\lambda}\right] \tag{4}$$

Based on the initiation of yielding, the computed yield moment ($(M_y)_{comp}$) of a homogeneous beam can be calculated by using the following equation:

$$(M_y)_{comp} = F_y S_e \tag{5}$$

where F_y = yield stress of steel
S_e = elastic section modulus of effective section

3.2. Alternative procedure using equivalent section

Eq. (5) may not apply directly to the hybrid beam fabricated from two different sheet steels because it is based on the assumption that the beam is homogeneous. For the case of hybrid beams fabricated from both sharp-yielding type of sheet steels, Eq. (5) could be used to calculate the yield moment if the element fabricated from the sheet steel with a lower yield strength reaches the yield point first.

To deal with the hybrid beam, the alternative procedure presented herein is to transform the built-up section consisting of different steels into an equivalent homogeneous beam. Because the tested beam specimens used in this study consisted of four groups (Groups W, Z, S, and K) which were fabricated from two different sheet steels with different stress-strain curve, the structural strength of these hybrid beams can be calculated by using the equivalent section concept.

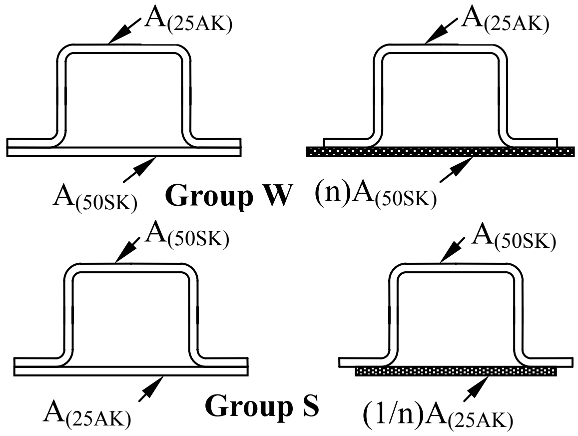

Figure 3a. Cross sections of equivalent section

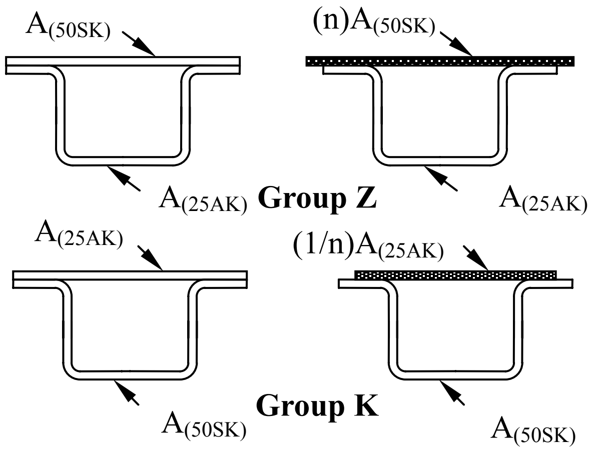

Figure 3b. Cross sections of equivalent section

As can be seen in Figure 3, the cross-sectional area of the plate fabricated from 50SK sheet steel (A_{50SK}) can be transformed to the equivalent area of 25AK sheet steel by using nA_{50SK} for Groups W and Z specimens. Similarly, for S and K specimens, the cross-sectional area of the plate fabricated from 25AK sheet steel (A_{25AK}) can be transformed to the equivalent area of 50SK sheet steel by using $(1/n)A_{25AK}$. The variable "n" is denoted as the modified ratio of the secant moduli given in Eq. (6).

$$n = \frac{n1 + n2}{2} = 1.72 \tag{6}$$

$$n1 = \frac{(\frac{\sigma_{pr}}{\varepsilon_{pr}})_{50SK}}{(\frac{\sigma_{pr}}{\varepsilon_{pr}})_{25AK}} = 1.05 \quad (7)$$

$$n2 = \frac{\left(\frac{\sigma_y}{\varepsilon_y}\right)_{50SK}}{\left(\frac{\sigma_y}{\varepsilon_y}\right)_{25AK}} = 2.39 \quad (8)$$

where σ_{pr} = proportional limit of sheet steel
σ_y = yield stress of sheet steel
ε_{pr} = strain of proportional limit
ε_y = strain of yield stress

Based on the equivalent section method, the yield moment of the hybrid beam can be estimated by assuming that the strain of the plane section in the beam varies directly with the distance from the neutral axis. The variable of n used in this investigation can be computed by using the constants, n_1 and n_2, based on the mechanical properties of these two sheet steels. The values of these two constants are listed in Eqs. (7) and (8). Figure 4 show the typical stress-strain relationships for 25AK sheet steel subjected to longitudinal tension under four strain rates of 10^{-4}, 10^{-2}, 10^{-1}, and 1.0 mm/mm/sec. The typical stress-strain relationships for 50SK sheet steel under tension are shown in Figure 5.

The proportional limits of 25AK and 50SK sheet steels were obtained by the offset method according to the AISI Commentary [6]. In the offset method, the proportional limit is the stress corresponding to the intersection of the stress-strain curve and a line parallel to the initial straight-line portion offset by a specified strain. The offset is usually specified as 0.01%. The yield strength of sharp-yielding sheet steel is determined by the stress where the stress-strain curve becomes horizontal. Therefore, the lower yield point of stress-strain diagram was used to determine the yield strength for 50SK sheet steel. For the gradual-yielding type stress-strain curve (25AK sheet steel), the yield strength was determined by the intersection of the stress-strain curve and the straight line drawn parallel to the elastic potion of the stress-strain curve at an offset of 0.2 percent.

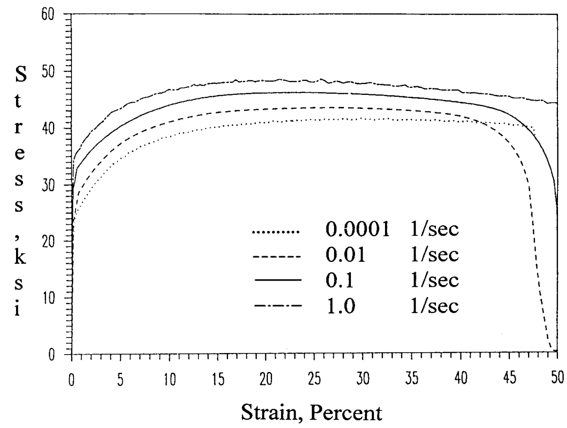

Figure 4. Stress-strain curves for 25AK sheet steel in longitudinal tension under different strain rates

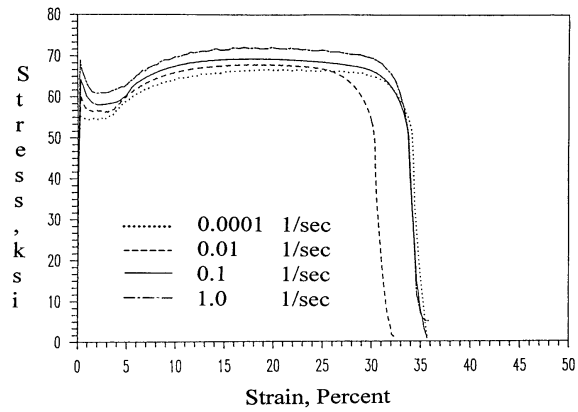

Figure 5. Stress-strain curves for 50SK sheet steel in longitudinal tension under different strain rates

According to the test results which were based on the readings obtained from the strain gages mounted on the top and bottom sides of beam specimens, it was found that the ratio of secant moduli of (n) may be used to locate the assumed neutral axis of the transformed cross section for the hybrid beam specimens fabricated from 25AK and 50SK sheet steels. Once the neutral axis was located, the computed yield moment of a beam corresponding to the initiation of yielding can be calculated by using the subsequent steps.

(a) For the case of initiation of yielding occurring in the top compression flange of the beam such as cases A, B, and C of Groups W and S, and case C of Group Z, the yield moment can be computed by the following steps:

1. The section is subdivided into a number of elements (a total of 12 segments were used in the calculation as shown in Figure 6).
2. A position of the neutral axis is assumed and the strain in the top fiber of the compression flange is assumed to be the yield strain of the steel. Based on these two values, the average strains in various elements are calculated.
3. From the tested stress-strain relationships obtained from material tests or the simulated stress-strain relationships discussed in the next section, the average stresses σ in various elements corresponding to such computed strains are found.
4. Calculate the effective width of the compression flange according to the yield stress of the steel in the compression flange.
5. Compute the area ΔA, including the effective section of compression flange, for each element.
6. Locate the neutral axis of transformed section by iteration until $\Sigma \Delta A \sigma = 0$ is satisfied.
7. The computed yield moment of a hybrid beam can be calculated by multiplying the force ($\Delta A \sigma$) and the distance for each element and summing up these values ($\Sigma \Delta A \sigma y$), in which y is the distance measured from the neutral axis to the centroid of each element.

(b) For the case of initiation of yielding occurring in the bottom tension flange of the beam such as cases A, B, and C of Group K and cases A and B of Group Z, the computed yield moment can be obtained by using the same steps discussed previously for the initiation of yielding occurred in the top compression flange except that steps (2) and (4) are changed as follows:

2. A position of the neutral axis is assumed and the strain in the bottom fiber of the tension flange is assumed to be the yield strain of the steel. Based on these two values, the average strains in various elements are calculated.
4. Calculate the effective width of the stiffened compression flange for the compression stress obtained from the yield strain of the steel in the tension flange and the assumed neutral axis.

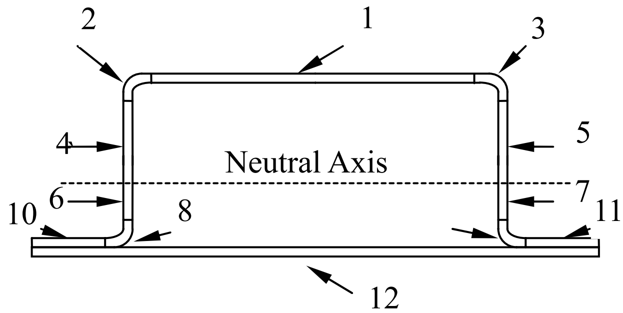

Figure 6. Location of elements for determination of the neutral axis of a beam specimen

It should be noted that for Groups Z and K specimens having compression stiffened plate, the effective width of the compression flange was calculated based on the actual thickness and width. The equivalent section can be computed on the basis of the effective sectional area of the stiffened plate and cross-sectional area of the hat section.

3.3. Stress-strain relationship

The types of stress-strain relationship for 25AK and 50SK sheet steels are different. As can be seen in Figures 4 and 5, the stress-strain relationship for 25AK sheet steel is the gradual-yielding type, and it is the sharp-yielding type for 50SK sheet steel. To obtain the stresses for each element from the calculated strains, the following empirical equations were derived from material tests and used to compute the stresses and strains for 25AK and 50SK sheet steels under different strain rates:

For 25AK sheet steel

$$\sigma = A + B/\varepsilon + C/\varepsilon^2 \quad (9)$$

For 50SK sheet steel

$$\sigma = D + E\varepsilon + F\varepsilon^2 \quad (10)$$

where σ = compressive stress (ksi)
ε = compressive strain expressed in percent (%)

when strain rate = 10^{-4} 1/sec:
A=23.64 B=-0.525 C=-0.008 D=1.403
E=334.7 F=-454.7

when strain rate = 10^{-3} 1/sec:
A=24.17 B=-0.137 C=-0.044 D=1.378
E=331.7 F=-431.2

when strain rate =10^{-2} 1/sec:
A=24.71 B=0.251 C=-0.080 D=1.350
E=328.6 F=-407.6

The strains used for determining the above equations were selected from the proportional limit to the yield point of steel. For the stresses below the proportional limit of the material, the following two empirical equations derived from material tests give the stress-strain relationships for 25AK and 50SK sheet steels:

For 25AK sheet steel

$$\sigma = (A/B)\varepsilon \quad (11)$$

For 50SK sheet steel

$$\sigma = (C/D)\varepsilon \quad (12)$$

when strain rate = 10^{-4} 1/sec:
A = 15.94 B = 0.065 C = 41.97
D = 0.153

when strain rate = 10^{-3} 1/sec:
A = 17.73 B = 0.078 C = 42.23
D = 0.154

when strain rate = 10^{-2} 1/sec:
A = 19.51 B = 0.086 C = 42.49
D = 0.155

From practical point of view, by applying Eqs. (9) to (12) in the calculation of yield moment seems too complicate. Since the types of stress-strain relationships for these two sheet steels (25AK and 50SK) are different, the approximate stress-strain relationships were adopted to calculate the computed yield moments as shown in Figure 7. By comparing the tested yield moments with the computed values calculated on the basis of the approximate stress-strain relationships for Group W specimens, it was observed that the computed yield moment can not provide a good prediction. The use of approximate stress-strain relationships as given in Figure 7 would result in conservative predicted yield moments particularly for the beams with small w/t ratios. For details, refer to Pan and Yu [12].

In order to simplify the calculation procedure, the simulated stress-strain relationships were constructed as shown in Figure 8. For the stresses below the proportional limit of the material, Eq. (13) can be used to represent the stress-strain relationships of sheet steels. Eq. (14) expresses the stress-strain relationships for the stress level between the proportional limit and the yield point of steel.

$$\sigma = \frac{\sigma_{pr}}{\varepsilon_{pr}} \times \varepsilon \tag{13}$$

$$\sigma = \left(\sigma_y - \sigma_{pr}\right)\frac{\left(\varepsilon - \varepsilon_{pr}\right)}{\left(\varepsilon_y - \varepsilon_{pr}\right)} + \sigma_{pr} \tag{14}$$

3.4. Discussion and summary

The computed yield moments are calculated based on the dynamic tensile and compressive yield stresses corresponding to the strain rate used in the test. The tested yield moments of beam specimens were determined from the product of bending arm (L/4) and one half of the yield load ($P_y/2$) as follows:

$$\left(M_y\right)_{test} = \frac{P_y L}{8} \tag{15}$$

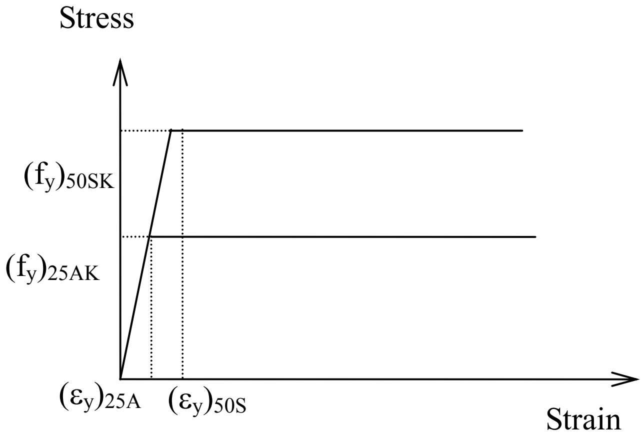

Figure 7. Approximate stress-strain relation-ships for 25AK and 50SK sheet steels

The summary of ratios of tested-to-computed yield moments calculated by different procedures for hat-shaped hybrid beams are listed in Tables 3 and 4. In Table 3, the computed yield moments are calculated by applying the alternative procedure with equivalent sections and simulated stress-strain curves. In Table 4, the computed yield moments are calculated by applying AISI Formulas – Eq. (5) and using equivalent sections.

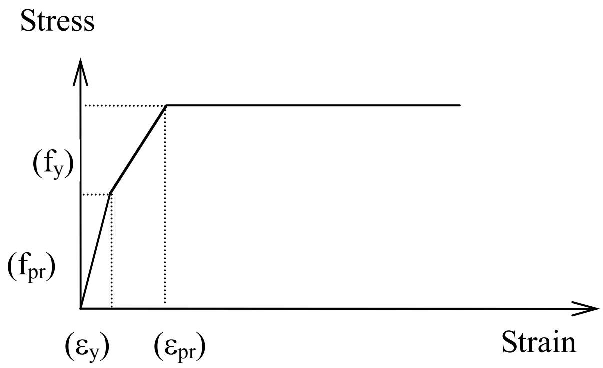

Figure 8. Simulated stress-strain relationship

Table 3. Ratios of tested-to-computed yield moments

	Based on dynamic tensile stresses		Based on dynamic compressive stresses	
Group (1)	Mean value (2)	Standard deviation (3)	Mean value (4)	Standard deviation (5)
W	1.007	0.092	1.140	0.119
Z	0.993	0.108	1.133	0.127
S	0.950	0.040	0.972	0.038
K	0.878	0.022	0.894	0.025

It is noted that the tested yield moment increases with increasing strain rate for specimens having similar w/t ratios. By adopting the equivalent section method in the calculation of yield moments, it was observed that the values of $(M_y)_{test}/(M_y)_{comp}$ ratios are quite close for the same case of Groups W and Z specimens having similar dimensions but tested under different strain rates. But for the Groups S and K specimens, the values of $(M_y)_{test}/(M_y)_{comp}$ ratios slightly increase with increasing strain rates for the same case of beam specimens. This is because the strain rate sensitivity for 25AK and 50SK sheet steels are different. As can be seen in Figure 3, the cross-sectional area of stiffened plate fabricated from 25AK sheet steel is reduced and transformed to 50SK material for Groups S and K specimens. In fact, the strain rate sensitivity of 25AK sheet steel is higher than the strain rate sensitivity of 50SK sheet steel. The ratios of tested-to-computed yield moments for case A of Groups W and Z are larger than the values for cases B and C. This is possibly due to the cold work of forming and the gradual yielding type of stress-strain curve for 25AK sheet steel. It is also noted that the ratios of tested-to-computed yield moments for all cases of Group K specimens are slightly less than the values for all cases of Group S, it is possibly due to the initial deformation of beam specimens which were caused by welding during the fabrication. The direction of initial deformation of entire beams is upward for Group S specimens and is down-ward for Group K specimens as mentioned in Pan and Yu [12].

Table 4. Ratios of tested-to-computed yield moments

	Based on dynamic tensile stresses		Based on dynamic compressive stresses	
Group (1)	Mean value (2)	Standard deviation (3)	Mean value (4)	Standard deviation (5)
S	0.978	0.041	0.996	0.039
K	0.916	0.034	0.930	0.030

According to Eq. (5), the computed yield moment was determined on the basis of the effective design width formula Eq. (4) with the extreme compression or tension stress at yield point for homogeneous beams. Table 4 shows the comparisons between the tested and computed yield moments for Groups S and K specimens, for which the computed values were calculated by applying the transformed section in Eq. (5). However, Eq. (5) could not be used in the calculation of yield moments for the specimens which the sheet steel used for analyzing equivalent sections is 25AK material. Since the stress-strain relationship for 25AK sheet steel is gradual-yielding type, the use of Eq. (5) would result in conservative yield moments particularly for the beams with small w/t ratios for Groups W and Z specimens.

4. Conclusions

A total of 72 hat-shaped beams were studied in this phase of study. The materials used in the fabrication of hybrid beams were 25AK and 50SK sheet steels. Four groups of hat-shaped beams were tested under different strain rates. The equivalent section concept and simulated stress-strain relationship were adopted in the calculation of yield moments for design purpose. Comparisons between the tested and computed values for yield moments were made in this paper. The following conclusions can be drawn for the hybrid beams fabricated from 25AK and 50SK sheet steels:

- The differences between the tested and computed values for yield moments are within 10 percent for most specimens. It seems that the equivalent section method can be used for the calculation of yield moment of hybrid beams.
- The alterative procedures presented in this paper give reasonable results for yield moment of hybrid beams.
- Both dynamic compressive and tensile stresses can be used for calculating the yield moment of hybrid beams.
- It was found that the computed yield moments based on tensile stresses are less conservative than the computed values based on compressive stresses.
- The effective cross-sectional area determined according to AISI Specification [6] can also be employed in the calculation of yield moment for hybrid sections.
- The simulated stress-strain relationships can be used in the calculation of yield moment of hybrid beams for both 25AK and 50SK sheet steels.

- If the sheet steel used for analyzing equivalent sections is a sharp -yielding type of stress-strain relationship, Eq. (5) can be adopted for calculating yield moment of hybrid beams.

In summary, the effective design width formulas and the dynamic material properties can be used for the calculation of load- carrying capacity of hybrid beams. Using an equivalent section method and applying the simulated stress-strain relationship, the alternative procedure discussed in paper can provide a reasonable approach for computing the yield moment of hybrid beams. For sheet steels used in practical design without the tested stress-strain relationships, the AISI formula Eq. (5) can be applied for calculating the yield moment of hybrid beams, when the sheet steel used for analyzing the transformed section has a sharp- yielding type of stress-strain relationship. Eq. (5) may also be used for computing the yield moment of hybrid beams with large w/t ratios, when the sheet steel used for analyzing the transformed section has a gradual-yielding type of stress-strain curve. However, the use of Eq. (5) could result in a conservative yield moment particularly for the compact beams with small w/t ratios.

For the case of hybrid beams fabricated from both sharp-yielding type of sheet steels, Eq. (5) could be used to calculate the yield moment if the element fabricated from the sheet steel with a lower yield strength reaches the yield point first. For other cases such as the hybrid beam fabricated from two different sheet steels with different stress- strain curve types, it seems that the procedure for calculating the yield moment of hybrid beam can be simplify by using equivalent- section concept, the suggested flow chart of calculating such hybrid hat-shaped beams is shown in the Appendix. For the case of hybrid beams fabricated from both gradual-yielding type of sheet steels, the yield moment may be computed by the alternative procedure with equivalent section method discussed in this paper.

The measured deflections under yield moments are between length/50 and length/100 for all tested specimens. It was observed from the tests that the deflection of the beam specimen under the ultimate load is quite large comparing with the deflection under yield load particularly for Groups Z and K specimens. Because of the complexity of the calculation of ultimate moment and excessive deflection, it is suggested that for practical design, the yield moment be used for the load-carrying capacity of hybrid beams.

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Notations

b=effective width of a compression element
E=modulus of elasticity of steel, 203 kN/mm^2 (29,500 ksi)
f=stress in the element
F_y=yield stress of steel
k=buckling coefficient
$(M_y)_{comp}$=computed yield moment
P_y=tested yield load
S_e=elastic section modulus of effective section
t=thickness of element
w=flat width of a compression element
λ=slenderness factor
σ_{pr}=proportional limit of sheet steel
σ_y=yield stress of sheet steel
ε_{pr}=strain of proportional limit
ε_y=strain of yield stress

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APPENDIX

Design Flow Chart for Calculating the Yield Moment of Hybrid Hat-Shaped Beam