Study of Thin-Walled Box Beams Crushing Behavior Using LS-DYNA®

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Abstract

This paper investigates the dynamic crushing behaviors of steel beams with box cross sections. Systematic parametric studies were conducted in order to reveal the effect of material properties, including strain hardening ratio and strain rate effect, length of the beam, and initial impact velocity on the crushing behaviors of the steel beams. A number of finite element models were constructed with various sets of parameters and used for crashworthiness analyses. Maximum crushing force, mean force, and specific energy absorption (SEA) were recorded after analyses and compared to reflect the influences of parameters. An explicit finite element solver, LS-DYNA®, was used in this study for modeling and analyses.

1. Introduction

Nowadays, thin-walled box-sectional beams are extensively used as energy absorbers in civil engineering, automotive engineering, shipbuilding, and other industries because of their excellent energy absorption capacity during impacts. Such beams are commonly made of steel, which is a strain rate sensitive material [1]. Jones [1] and Han et al. [2] discussed the effects of strain hardening and stain rate sensitivity on crash responses of circular steel tubes. In this paper, the strain hardening and strain rate effects on steel box-sectional beams are examined.

Crush behaviors of box-sectional beams under axial compression have been thoroughly illustrated in previous researches [3-5]. In those literatures, researchers derived equations indicated that mean crushing force can be evaluated based on beam's material properties and cross-sectional dimensions. Nevertheless, peak crushing force occurs in crashes receives more attention because in automotive engineering the peak crushing force directly affects occupant comfort and human safety. According to our experiences, the peak crushing force is also related to the beam's total length and initial impact velocity as well as the beam's material and cross-sectional dimensions. One objective of this study is to reveal the effects of beam's length and initial velocity on the peak crushing force.

In this study, a number of finite element (FE) models were created for the steel box-sectional beams with different lengths. These FE models then were used for crashworthiness analyses and during the analyses, different initial impact velocities were assigned. The effects of material's strain hardening ratio and strain sensitivity rate were firstly discussed. Next, for the steel beams with box sections, which have both strain hardening and rate sensitivity, the effects of beam length and impact velocity on the beam's crushing behaviors were demonstrated based on the analyses results of peak crushing force, mean crushing force, and energy absorption capacity (SEA). LS-DYNA was used to generate the FE models and run the numerical analyses.

2. Finite element modeling and numerical analysis

Finite element models were created for the steel box-sectional beams. These beams have fixed cross-sectional dimensions (45mm×45mm and wall thickness (t) is 2.0mm) and various lengths, which varied from 200mm to 400mm. The commercial explicit code, LS-DYNA, was used for generating the FE models as well as running the dynamic analyses. As shown in figure 1, the FE models were meshed with 4-node Belytschko-Tsay shell element with five integration points through its thickness. Material model 3 of LS-DYNA (MAT_PLASTIC_KINEMATIC) was selected to model such beams. The material properties of the mild steel are: density ρ = 7830kg/m^3, Young's modulus E = 207GPa, Poisson's ratio υ = 0.3, yield stress σ_y = 200MPa. On finding the effects of strain hardening and strain rate, 4 cases were considered: case 1-steel with neither strain hardening nor strain ratio (O/O); case 2-steel with strain hardening but rate effects (H/O); case 3-steel with rate effects but strain hardening (O/R); case 4-steel with both strain hardening and rate effects (H/R). Different settings corresponding to above cases are listed in table 1.

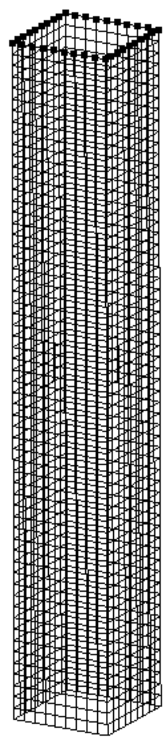

Figure 1. FE model for a steel box-sectional beam

Table 1. Material models for strain hardening and rate effects

	Strain hardening effects		Strain rate effects	
Parameters	E_t	β	C	P
Yes	1.5	1	40	5
No	0	0	0	0

In table 1, E_t is tangent modulus, which is ratio between material's ultimate stress and its initial yield stress (σ_u/σ_0), and it determines the strain hardening effect together with hardening parameter β (as shown in figure 2). C and P are two strain rate parameters and in this LS-DYNA model the influence of material strain rate sensitivity is considered using Cowper and Symonds model [1]:

$$\sigma_0' = \sigma_0\left(1+\left(\frac{\dot{\varepsilon}}{C}\right)^{1/P}\right) \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate and from that equation it is shown that during dynamic crushing, the original yield strength σ_0 is replaced by the dynamic flow stress σ_0' due to the strain rate effects.

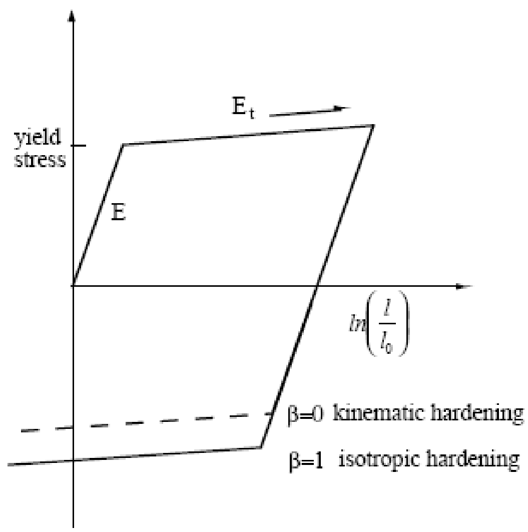

Figure 2. Strain hardening effects modeled in LS-DYNA [6]

Dynamic crushing analyses were performed on the FE models and during the analysis, these beam models impact onto a rigid wall at different initial speeds (5m/s, 10m/s, and 15m/s). Analysis results were collected afterwards and the peak crushing force, mean crushing force, and SEA are considered as most important data in sketching the beams' crushing behaviors. Important results are listed throughout table 2 to 4.

Table 2. Summary of dynamic crushing analysis on steel beams (L = 200mm)

Initial velocity	Material case #	Peak force	Mean force	SEA
5m/s	1 (O/O)	68.4kN	30.8kN	3.5kJ/kg
	2 (H/O)	68.4kN	46.2kN	5.2kJ/kg
	3 (O/R)	149.4kN	54.3kN	7.2kJ/kg
	4 (H/R)	158.3kN	90.8kN	9.5kJ/kg
10m/s	1 (O/O)	81.7kN	33.9kN	8.5kJ/kg
	2 (H/O)	81.9kN	47.1kN	10.7kJ/kg
	3 (O/R)	155.2kN	64kN	17kJ/kg
	4 (H/R)	168kN	94.4kN	21kJ/kg
15m/s	1 (O/O)	82.1kN	35.6kN	12.2kJ/kg
	2 (H/O)	82.6kN	47.2kN	17.2kJ/kg
	3 (O/R)	205.5kN	64.6kN	25kJ/kg
	4 (H/R)	205.5kN	97.5kN	32.3kJ/kg

Table 3. Summary of dynamic crushing analysis on steel beams (L = 300mm)

Initial velocity	Material case #	Peak force	Mean force	SEA
5m/s	1 (O/O)	72kN	32.1kN	3.5kJ/kg
	2 (H/O)	72.3kN	46.3kN	5kJ/kg
	3 (O/R)	145.9kN	55kN	6.9kJ/kg
	4 (H/R)	150.3kN	86.6kN	9.1kJ/kg
10m/s	1 (O/O)	81.7kN	36.9kN	8.7kJ/kg
	2 (H/O)	81.9kN	50.2kN	11kJ/kg
	3 (O/R)	153.3kN	66.2kN	16.9kJ/kg
	4 (H/R)	161.1kN	92.9kN	20kJ/kg
15m/s	1 (O/O)	82.1kN	36.2kN	12.3kJ/kg
	2 (H/O)	82.6kN	48.9kN	14.3kJ/kg
	3 (O/R)	205.6kN	69.5kN	25.7kJ/kg
	4 (H/R)	205.6kN	94.7kN	30.9kJ/kg

Table 4. Summary of dynamic crushing analysis on steel beams (L = 400mm)

Initial velocity	Material case #	Peak force	Mean force	SEA
5m/s	1 (O/O)	71.9kN	31.5kN	3.6kJ/kg
	2 (H/O)	72.1kN	46.6kN	5.2kJ/kg
	3 (O/R)	144.4kN	55.1kN	6.9kJ/kg
	4 (H/R)	153.2kN	87.5kN	9.5kJ/kg
10m/s	1 (O/O)	81.7kN	34.8kN	7.6kJ/kg
	2 (H/O)	81.8kN	49.2kN	11.3kJ/kg
	3 (O/R)	148.3kN	66.3kN	16.8kJ/kg
	4 (H/R)	159.3kN	95.5kN	20.8kJ/kg
15m/s	1 (O/O)	82.1kN	34.6kN	11.9kJ/kg
	2 (H/O)	82.4kN	50.3kN	17.5kJ/kg
	3 (O/R)	210.1kN	66.9kN	25kJ/kg
	4 (H/R)	210.1kN	97.7kN	32kJ/kg

3. Effects of strain rate and strain hardening

It is known that steel is a strain rate sensitive material with high strain hardening ratio, thus the effects of both strain rate and hardening have to be considered in analysis of steel beams. From table 2 to 4, following observations can be made:

1. Strain hardening doesn't apparently affect the peak crushing force but cause increased mean crushing force and higher energy absorption capability. Obviously, the strain hardening effect is helpful in improving box-sectional beam's crushing performance.
2. Compare to the models without strain rate effect, the peak crushing force, mean crushing force, and SEA are much higher for the steel beams with strain rate effect. The higher peak crushing force due to the strain rate effect may affect occupant's conformability and safety in vehicle design.
3. For the steel beam models with strain rate effect, the of peak crushing force increases much faster at higher impact velocity (v > 10m/s) than lower velocity (v < 5m/s). This is because under the effect of strain rate, with the increase of impact velocity, the corner crushing load grows larger, which causes the highly increasing peak crushing force [2].

The conclusions drawn here perfectly accord with the observations made by Han et al. [2] from a series of quasi-static and dynamic impact experiments. Furthermore, according to Jones [1], the strain hardening and strain rate effects could be decoupled as

$$\sigma_0' = \sigma_0 \left(1 + \left(\frac{\dot{\varepsilon}}{C} \right)^{1/P} \right) g(\varepsilon) \tag{2}$$

where g(ε) stands for strain hardening and in our study it is taken as linear (through E_t).

4. Effects of beam length and impact velocity

As illustrated before, both strain rate and strain hardening effects have to be accounted when modeling steal beams. In this section, the analysis results from the models with strain rate and strain hardening were plotted in order to find the effects of beam length and impact velocity on the models' crushing behaviors. Important results are plotted throughout figure 3 to 5.

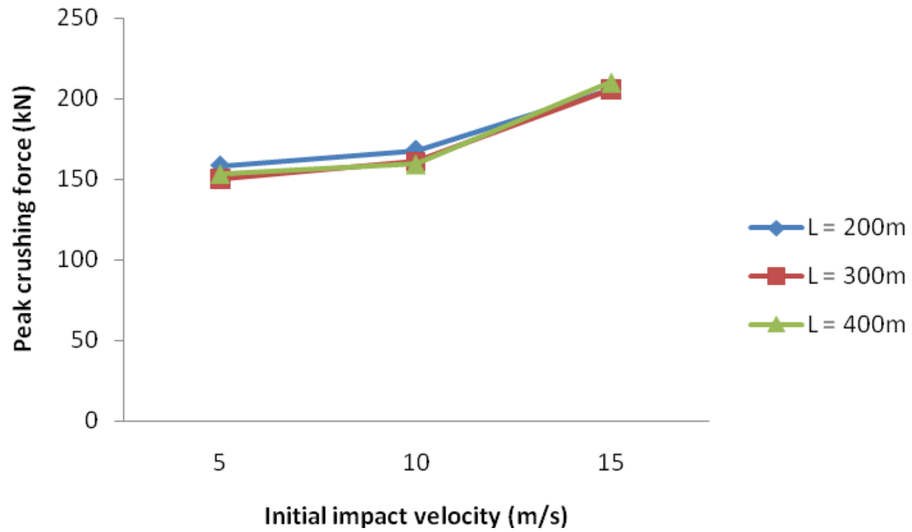

Figure 3. Peak crushing forces under various beam lengths and impact velocities

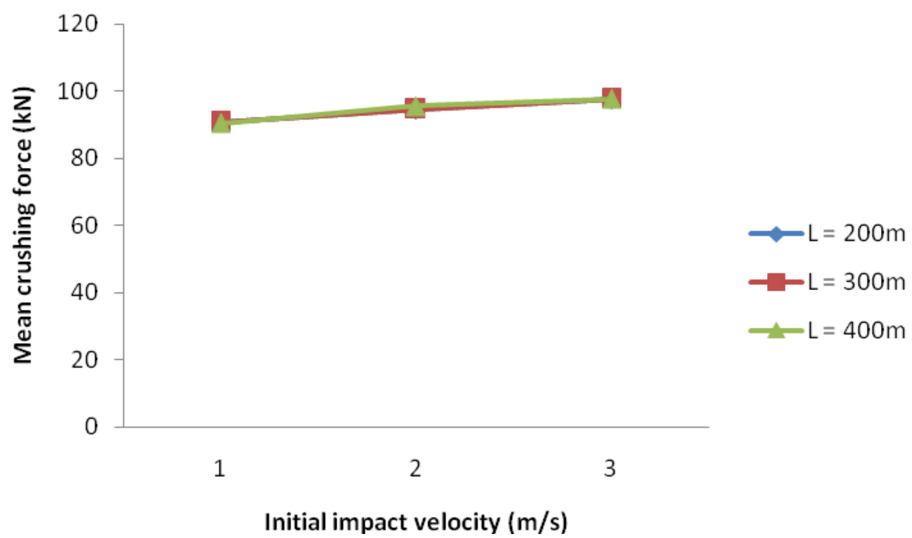

Figure 4. Mean crushing forces under various beam lengths and impact velocities

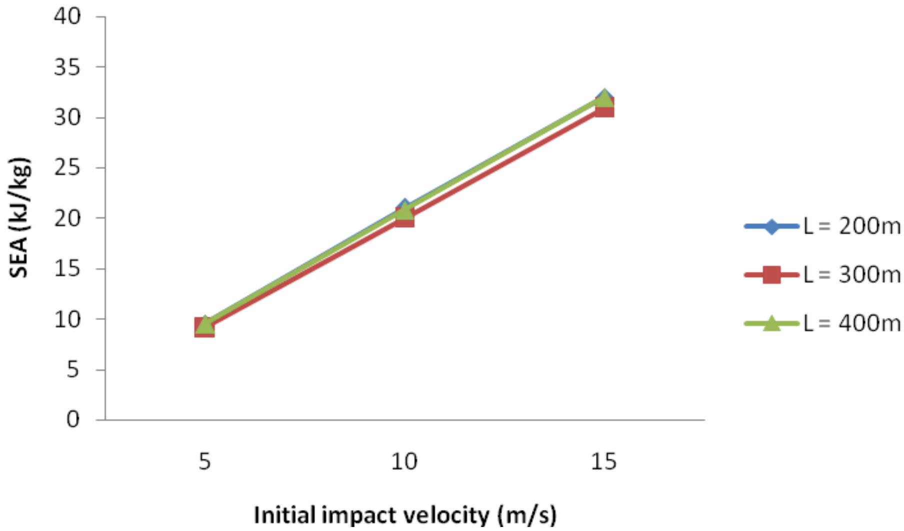

Figure 5. SEA under various beam lengths and impact velocities

4.1 Effects of beam length

From figure 3 to 5 it is shown that the effect of beam length on its crushing response is very small. Peak crushing force, mean crushing forces, and SEA are almost invariant for beams with different lengths (from 200 – 400mm). Therefore, in predicting thin-walled box-sectional beams' crushing behaviors, the effect of beam length can be neglected and these beams will show a similar collapse mode under different lengths.

4.2 Effects of impact velocity

Unlike the beam length, the initial impact velocity apparently affects the peak crushing force and the SEA. As mentioned before, the increasing initial velocity leads to a higher peak crushing force. At higher initial velocity (>10m/s), the increment of peak crushing force becomes higher because the corner crushing load grows larger at high impact velocities. Figure 5 shows that when the initial velocity increases, the SEA increases linearly. However, the initial velocity doesn't arouse a noticeable change in the mean crushing force: the mean crushing force slightly increases with the increasing velocity.

4.3 Discussions

From above discussion, it can be seen that in predicting the thin-walled box-sectional beam's crushing behaviors, its mean crushing force can be assumed as independent of beam length and initial velocity. According to Wierzbicki and Abramowicz's theory [3], the mean crushing force can be evaluated based on the beam's material and its cross-sectional dimensions, as shown in Eq. (3).

$$P_m = 52.22\left(\frac{\sigma_0 t^2}{4}\right)\left(\frac{a}{t}\right)^{0.37} \tag{3}$$

In our study, without regard to the effects of strain hardening and strain rate, the mean crushing forces obtained from different lengths and under different impact velocities vary from 30.8 to

36.2kN. Substitutes a = 45mm, t = 2mm, and the yield stress = 200MPa into above equation, the evaluated mean crushing force value equals 33.1kN, which agrees to our analysis results very well. Similarly, when the strain hardening ratio takes 1.5, the mean crushing force is calculated as 49.6kN using Eq. (3), while the results yielded from the crashworthiness analysis lie between 46.2 and 50.3kN (table 2 to 4).

Practically, as shown in figure 4, with the effect of strain rate, the mean crushing forces are slightly enhanced due as the impact velocity increased. The tiny effect of the impact velocity on the mean crushing force due to the strain rate sensitivity is described by Jones [1] as

$$P_m = 52.22\left(\frac{\sigma_0 t^2}{4}\right)\left(\frac{a}{t}\right)^{0.37}\left\{1+(0.33V_0/aC)^{1/P}\right\} \tag{4}$$

After substituting C = 40 and P = 5 in that equation, the mean crushing forces under different impact velocities 5m/s, 10m/s, and 15m/s are 57.9kN, 62.1kN, and 64.9kN, respectively. The mean crushing forces obtained from the dynamic numerical analyses vary from 54.3 to 55.1kN (V_0 = 5m/s), 64 to 66.3kN (V_0 = 10m/s), and 64.6 to 69.5kN (V_0 = 15m/s). Both sets of results still correlate to each other. Similar observations can be obtained considering the effects of both strain hardening and strain rate. By taking strain hardening ratio as 1.5, the mean crushing forces evaluated from Eq. (4) with the different impact velocities increase 1.5 times, which are 86.8kN, 93.2kN, and 97.4kN,. And the numerical results lie between 87.5 to 90.8kN (V_0 = 5m/s), 92.9 to 95.5kN (V_0 = 10m/s), and 94.7 to 97.7kN (V_0 = 15m/s). The comparison results verify Jones' crash theories and again testify that during the axial crushing, the effects of strain hardening and strain rate can be decoupled.

The relationship between the SEA and initial impact velocity is almost linearly, therefore, the energy absorption capability SEA under different impact velocities can be easily predicted employing the linear relationship. Nevertheless, the relationship between the peak crushing force and the initial velocity has to be derived based on the results listed in table 2-4 by performing a nonlinear regression analysis.

5. Conclusions

In this paper, the effects of strain hardening and strain rate on the crash response of the steel thin-walled beams with box sections are studied. It is concluded that the strain hardening improves the mean crushing force as well as the SEA while doesn't affect the peak crushing force. In another hand, the strain rate effect leads to much higher peak crushing force, mean crushing force, and SEA. A systemic crash analyses were performed to investigate the influences of the beam length and initial impact velocity on the crushing behaviors of the thin-walled box-sectional beam. The results show that the beam length does not significantly affect such beam's crushing behavior and as the initial velocity increased, both peak crushing force and SEA increased apparently. This study also verifies that LS-DYNA is an efficient tool in computational modeling and analysis.

References

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