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Design of Multi-Cell Tailored Property Columns Under Oblique Loading

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Abstract

In this study, the crashworthiness performance of a multi-cell column designed from B1500HS boron steel with three different hardness values and six different regional hot-formed designs were compared in terms of passenger safety. Energy absorption and peak crushing force values of the columns were examined by impact simulations under oblique loading. “T25 heat-treated column” gave the highest energy absorption value, while "O25 heat-treated column" gave the lowest peak crushing force value. Regional hot-formed columns’ energy absorption and peak crushing force values resulted in between these two homogeneous heat-treated columns, except for the fifth and eighth designs. It has been shown that regional hot forming has a significant effect on the crashworthiness performance of the multi-cell columns under oblique loading.

Keywords: Boron steel; crashworthiness; energy absorption (EA); multi-cell column; oblique loading; peak crushing force (PCF); tailored property

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1. Introduction

Studies on the design of vehicle structural components focus on lighter designs but have higher crash safety and will meet legal requirements. Thin-walled structures are widely used for these purposes [1-4]. Crash boxes are thin-walled structures and are positioned behind the front bumper for less damage to the passenger compartment in the event of a frontal collision. They absorb the kinetic energy of the vehicle to a certain extent by undergoing plastic deformation. [5]. The location of the crash boxes in a vehicle is given in Figure 1.

Fig. 1. Location of crash boxes in a vehicle [6]

The collision performance of thin-walled structures varies depending on their design. Therefore, different design proposals are made by comparing the collision characteristics of thin-walled structures with different shapes and designed using different materials [7]. Multicellular columns are thin-walled structures, and although there are many studies in the literature on the energy dissipation performance of these structures [8-11], studies on regional hot-formed multi-cell columns are limited [12]. There are limited experimental studies on regional heat treatment of thin-walled structures in the literature. The axial crush behavior of the regional heat-treated crush rails was investigated. A non-tailored (fully martensitic) and three tailored (have soft zones) rails' crash experiments were applied. Non-tailored rail absorbed the highest energy but tended to break. The energy absorption of regional heat-treated rails was high, and the tendency to fracture was less. Local heat treatment can ensure that the structural part can absorb energy without failure [13].

No study was found in the literature on regional hot-formed multi-cell columns under oblique loading when the studies were examined. In the study, the crash performance of a four-cell column designed from B1500HS boron steel for three different hardness values was compared in terms of passenger safety using the finite element analysis method. At the same time, collision analyzes were carried out for designs in which different parts of the column have different hardness values (regional hot-formed). The results were compared in peak crushing force (PCF) and energy absorption (EA) values. "T25 heat-treated column" gave the highest EA value of 30.28 kJ, while the lowest PCF value was 251.19 kN with "O25 heat-treated column". "T450 heat-treated column" and regional hot-formed columns generally performed between these two columns. In the following sections, information is given about the literature research, the technique applied, and the results obtained.

2. Literature Survey

There are many studies in the literature on the energy absorption performance of multi-cell columns. The collision behaviors of different multi-cell hexagonal columns were investigated under axial and oblique collision [8]. Another study evaluated cell number and topological configuration on collision performance in multi-cell structures [9]. The energy absorption characteristics of the so-called bionic honeycomb thin-walled structure (BHTS) columns, inspired by the internal structure of the ladybeetle, were investigated [10]. Inspired by the shape of the spider web, columns with different geometries were designed, and their collision performances were compared [11].

Although there are many studies on the collision behavior of multi-cell columns, studies on regional hot-formed multicellular columns are very limited. It has been shown that the collision performance of multi-cell columns under axial crush and lateral bending is better than conventional columns. Collision performance improved when the number of cells increased [12]. There is no study in the literature on regional hot-formed multi-cell columns under oblique loading. In the study, the collision performance of a four-cell column designed from B1500HS boron steel was compared for three different hardness values and regional hot-formed designs.

3. Impact Analysis Under Oblique Loading

B1500HS boron steels are hot formable steels. B1500HS boron steel sheets were heat-treated at different die temperatures, and different hardness values were obtained. Die temperature 450 °C and 25 °C, are denoted as T450 and T25, respectively. O25 shows the cooling state in an open furnace [14]. In this study, the crash performance of a four-cell column designed from B1500HS material with three different hardness values and six different regional hot-formed designs were compared in terms of passenger safety. The designed columns are shown in Figure 2.

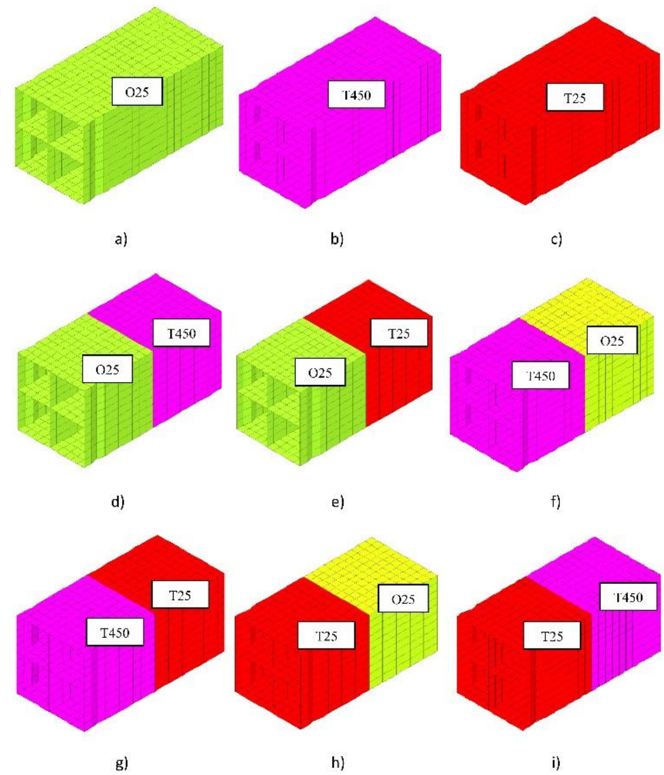

Fig. 2. a) O25 heat-treated column b) T450 heat-treated column c) T25 heat-treated column d) Upper part O25 and lower part T450 heat-treated column e) Upper part O25 and lower part T25 heat-treated column f) Upper part T450 and lower part O25 heat-treated column g) Upper part T450 and lower part T25 heat-treated column h) Upper part T25 and lower part O25 heat-treated column i) Upper part T25 and lower part T450 heat-treated column

Impact simulations were performed with a four-cell column-rigid plate finite element model. HyperCrash software was used as a preprocessor in the analysis. In the model, shell elements, which are preferred in sheet metal structures, were used, and the average element size was taken as 5 mm. In the column model, QBAT element type was used, 2 mm was taken as the wall thickness, and five was chosen as the number of integration points throughout the thickness. The rigid plate wall thickness was taken as 0.2 mm. The model has a total of 1600 elements. Type 7 and Type 11 contact types were preferred for contact definitions, and the friction coefficient was taken as 0.2. The Johnson-Cook material model was used in the column model, and the parameters of B1500HS steel, which was subjected to O25, T450, and T25 heat treatments, are given in Table 1.

Table 1. Johnson-Cook material model constants for O25, T450, and T25 heat treated B1500HS boron steel [14]

Heat treatment type	O25	T450	T25
Density (ton/mm^{-3})	7.85x10^{-9}	7.85x10^{-9}	7.85x10^{-9}
Young's modulus (MPa)	210000	210000	210000
Poisson's ratio	0.33	0.33	0.33
Yield stress (MPa) [a]	305	660	890
Strain hardening coefficient (MPa) [b]	610	770	1150
Strain hardening exponent [n]	0.42	0.38	0.22

A square-section rigid plate with 100 x 100 mm dimensions and 100 kg mass was impacted to the fixed column with a velocity of 5 m/s. The total length of the column is 100 mm, and the 10 mm part under it is fixed. This boundary condition is provided by fixing the column nodes. The rigid plate normal is in the x-y plane and makes an angle of 10° with the axis of the column. Radioss software was used as the solver, and 12 ms was taken as the solution interval to obtain the EA and PCF values. The collision model is given in Figure 3.

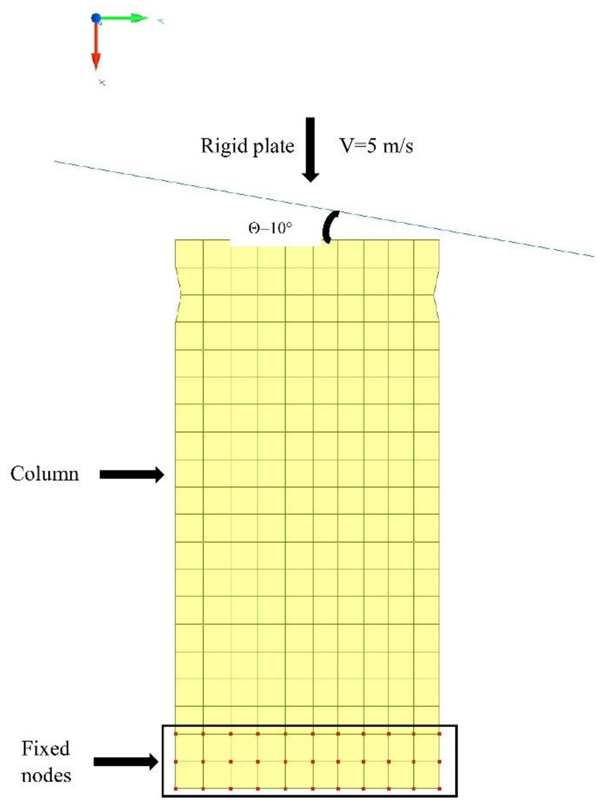

Fig. 3. Impact model

Deformation patterns for the "T25 heat-treated column" are given in Figure 4. Progressive folding has occurred, which is desirable for such structures.

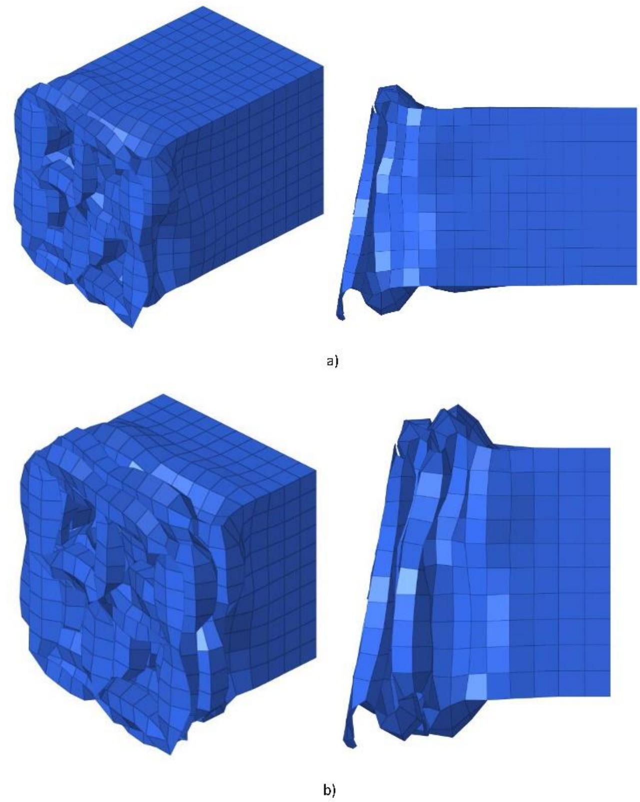

Fig. 4. Deformation patterns for "T25 heat-treated column": a) 6th ms b) 12th ms

EA is the total energy absorption of the column during plastic deformation:

$$EA = \int_0^{x_{max}} f(x)dx \qquad (1)$$

In equation (1), f(x) is the instantaneous impact force between the rigid plate and the column, and x_{max} is the maximum displacement of the rigid plate [15].

PCF is the highest loading force that occurs during the deformation of the column [16]. A lower PCF value means a lower risk of injury in accidents. The EA and PCF values obtained from the collision analysis of the columns are given in Table 2.

Table 2. EA and PCF results of the multi-cell columns

Design number	Column type	EA (kJ)	PCF (kN)
1	O25 heat-treated column	12	251.19
2	T450 heat-treated column	20.01	400.18
3	T25 heat-treated column	30.28	610.54
4	Upper part O25 and lower part T450 heat-treated column	14.79	393.28
5	Upper part O25 and lower part T25 heat-treated column	18.08	637.58
6	Upper part T450 and lower part O25 heat-treated column	14.96	392.8
7	Upper part T450 and lower part T25 heat-treated column	23.91	606.05
8	Upper part T25 and lower part O25 heat-treated column	19.01	618.65
9	Upper part T25 and lower part T450 heat-treated column	23.87	574.27

When the table is examined, “T25 heat-treated column” gave the highest EA value with 30.28 kJ, while "O25 heat-treated column" gave the lowest PCF value with 251.19 kN. O25, T450 and T25 heat-treated column’s yield stress values are 305, 660 and 890 MPa respectively. It is seen that EA and PCF values increase together as yield strength increases in homogeneous heat-treated columns (first three designs). It is desirable to have a high EA value in such structural components but a low PCF value. In regional hot-formed designs (designs 4-9), EA and PCF values resulted between the first and third designs, except for the fifth and eighth designs. The fifth design and eighth designs gave a PCF value of 637.58 and 618.65 kN, respectively. These values are higher value than the third design. The designer can select an appropriate design from the table, prioritizing the importance between EA and PCF. For example, if the designer wants the EA value to be as high as possible but does not want the PCF value to exceed 600 kN, it is appropriate to choose the ninth design. When the results are examined, it is seen that the regional hot forming has a significant effect on the crashworthiness performance of the columns.

4. Conclusions

Within the scope of the study, the crash performance of a multi-cell column designed from B1500HS boron steel for three different hardness values was compared in terms of passenger safety. At the same time, collision simulations were performed for six different regional hot-formed column designs. The results were compared in terms of EA and PCF values. "T25 heat-treated column" gave the highest EA value of 30.28 kJ, while the lowest PCF value was 251.19 kN with "O25 heat-treated column". In homogeneous heat-treated columns (first three designs), EA and PCF values increased together as yield strength increased. In regional hot-formed designs (designs 4-9), EA and PCF values resulted between the first and third designs, except for the fifth and eighth designs. The fifth design and eighth designs gave a PCF value of 637.58 and 618.65 kN, respectively. These values are higher value than the third design. The designer can select an appropriate design from the table, prioritizing the importance between EA and PCF. It has been shown that regional hot forming has a significant effect on the impact performance of the multi-cell columns under oblique loading.

Nomenclature

EA	:	energy absorption (J)
f(x)	:	impact force (N)
PCF	:	peak crushing force (N)
V	:	velocity (m/s)
x_{max}	:	max displacement (m)
Θ	:	impact angle (°)

Conflict of Interest Statement

The author declares that there is no conflict of interest.

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