Science & Technology Development Journal – Engineering and Technology 2025, 8(3):2592-2599

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Research Article

Dynamic axial crushing behaviour of thin-walled prismatic structures under high-velocity impact loading: Consideration of strain rate effect

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ABSTRACT

This paper presented a study of the dynamic behavior of mild steel St37 thin-walled columns subjected to high-velocity axial impact. Mild steel St37 was a strain rate sensitive material since its stress-strain relation depent on the rates of loading. Two groups of thin-walled columns were used in this study, i.e. one group of material model had strain rates with up to 100 s^{-1} (group 1) and another had strain rates with up to 4500 s^{-1}(group 2). The study was conducted by using theoretical solution and finite element analysis for impact speeds of 20 m/s, 30 m/s, 40 m/s and 50 m/s. The instantaneous and mean crushing forces of the thin-walled columns were predicted and compared in terms of the effect of strain rates and initial velocity impact conditions. For impact speed less than 20 m/s, the results shown that there were no significant differences with respect to crushing forces and energy absorption capability for both materials of (group 1) and (group 2). However, for impact speed higher than 20 m/s, the structural model of group 2 with strain rates up to 4500 s^{-1} pointed out higher crushing forces, peak force and energy absorption than those in group 1. Consequently, the impact analysis under high-velocity impact should use high strain rates material model. Moreover, the comparison between theoretical and numerical studies also shown a good agreement in terms of mean crushing forces at various high-velocities impact.

Key words: Crush behavior, Crashworthiness, Impact, Thin-walled structures, Strain rate effect

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History

- Received: 20-09-2023
- Revised: 09-11-2024
- Accepted: 05-08-2025
- Published Online: 15-08-2025

DOI :

https://doi.org/10.32508/stdjet.v8i3.1206

INTRODUCTION

Thin-walled prismatic structures have been used as energy absorption components for crashworthiness applications in vehicles with many advantages. These structural components have to absorb sufficient energy as well as reduce the impact loading to protect the passengers in order to avoid excessive deceleration during a crash [1,2]. Under low velocity impact, the thin-walled structures have axial crushing responses with ignorable influence of loading rate. In fact, many scholars show the insignificant for the changes of material properties caused by effect of strain rates under low velocity impact conditions [3–8]. In contrast to low velocity impact, the structural materials will undergo higher load and deformation in dynamic plastic buckling progression under high-velocity impact. Due to an increase in flow stress of strain rate sensitive thin-walled structures, high-velocity impact will impulse energy absorbing capability of structures [9–14].

According to L. L. Tam and C. R. Calladine [10], the inertia and strain rate effect were carried out by evaluating two types of materials: aluminium and steel. Abramowicz and Norman Jones [11,12], the square and circular tubes were studied under dynamic axial crushing. The authors mentioned about material strain rate effects even when the loading are in quasi-static case. Thus, they suggested that it was significant to replace the static yield stress by dynamic yield stress in analysis for strain rate sensitive materials. However, the range of impact velocities in their research were not high, i.e. from 6.35 m/s to 10.38 m/s. Chih-Cheng Yang et al. [13] focused on the dynamic progressive buckling of square tubes. For mild steel, they concluded that the influence of material strain rate sensitivity was retained for dynamic behaviour. Masahiro HIGUCHI et al. [14] presented the dynamic behaviour of circular tube subjected to high-impact loading. Although a material of aluminium alloy was used in his study, he suggested that an increase in initial impact velocity improved the absorbed energy through compressive deformation.

Most of the above studies attempted to understand the dynamic behaviour of thin-walled structures including the effect of strain rates under low velocity. It is clear that aluminium was an insensitive strain rate material, thus the influences of strain rate on the en-

Cite this article : Tran H, Le-dinh T, Tran-van T, Gunawan L, P. Santosa S, Jusuf A, Dirgantara T. **Dynamic axial crushing behaviour of thin-walled prismatic structures under high-velocity impact loading: Consideration of strain rate effect**. *Sci. Tech. Dev. J. – Engineering and Technology* 2025; 8(3):2592-2599.

ergy absorption capability was not necessary to exist in analysis model. The present work is to evaluate comprehensively the axial crushing behavior of thin-walled mild steel St37 square columns under high-velocity impact conditions. The changes of initial velocities brought about the changes in structural materials which were predicted through theoretical and numerical studies. This study is carried out by approaching at impact speeds of 20 m/s, 30 m/s, 40 m/s and 50 m/s with the strain rates levels up to 100 s^{-1} and 4500 s^{-1}.

THEORETICAL ANALYSIS

Attention in this paper is focusing on dynamic impact under high-velocity, thus theoretical analysis process is certainly based on dynamic prediction. In particularly, this paper would like to investigate the axial crushing behavior of thin-walled structures in symmetric in-extensional mode [11,12] because this mode is typical crushing mode of thin-walled structures under axial impact conditions. Several formulas‘ for obtaining the dynamic mean crushing force, mean plastic flow stress, total energies absorbing, folding length and crushing length were described by W. Abramowicz and Norman Jones [11] and developed by T. Wierzbicki and Santosa [4] et al.

$$\frac{\bar{P}_m^d}{M_0} = 52.22\left[1+\left(\frac{0.33v}{bC}\right)^{\frac{1}{q}}\right]\left(\frac{b}{t}\right)^{\frac{1}{3}} \quad (1)$$

$$M_0 = \frac{1}{4}\sigma_0 t^2 \quad (2)$$

$$\sigma_0 = \sqrt[3]{\frac{2\sigma_y\sigma_u^2}{(n+1)^2(n+2)}} \quad (3)$$

where: P_m is mean crushing force. M_0 is fully plastic moment, σ_o is dynamic flow stress, σ_y and σ_u are dynamic yield strength and ultimate strength. v (m/s) is impact velocity. Strain hardening exponent n is obtained from experimental data, i.e. stress-strain curves by using curved fitting process and is shown in Table 1.

Table 1: Strain hardening exponent at various strain rates

Strain rate (s-1)	0.001	0.1	1	10	100	2500	3500	4500
n	0.35	0.3	0.23	0.2	0.18	0.101	0.09	0.081

C and q are Cowper-Symonds coefficient which are considered in constitutive equation section. b, t are the width and thickness of column.

Constitutive equation

The essential Cowper-Symonds equation was widely used to perform the material behavior at varying different strain rates [11,12].

$$\frac{\sigma_{yd}}{\sigma_{ys}} = 1+\left(\frac{\varepsilon}{C}\right)^{\frac{1}{q}} \quad (4)$$

where: C and q are the Cowper-Symonds coefficients, ε is strain rate, σ_{yd}, σ_{ys} are dynamic yield stress and static yield stress respectively. According to Cowper and Symonds (1957), for mild steel, C and q correspond value of 40.4 and 5. However, it is clear that C and q in Eq. (4) are obtained based on test data and at each strain rate and those values will change at different reference stresses or various strain rates. In this work, by applying the captured data from tensile test as seen in Figure 3, the Cowper-Symonds coefficients are modified by using curve fitting process and shown in Table 2.

Table 2: Cowper-Symonds coefficients for mild steel St 37

Material	Strain rate (s-1)	C	q
Mild steel St37	2500	40.92	3.05
	3500	39.05	3.1

Material characteristic

In order to assess the effect of strain rate under high-velocity impact with respect to the crushing resistance of thin-walled square columns, two groups of material models were used in numerical analysis. Under various high-velocities, the properties of strain rates sensitive materials will change and affect the energy absorption capability of thin-walled structures during axial crushing. Therefore, to get these properties for simulations, a series of tensile tests at high strain rates were conducted by using the same material specimens, i.e. quasi-static tensile test with strain rates 10-3 s-1 and dynamic tensile test with a range of strain rates 0.1, 1, 10, 100 s^{-1}. It was shown in Figure 1 (a) and (b). For high strain rates of 2500, 3500 and 4500 s^{-1}, the material properties of mild steel St37 were carried out by using Split Hopkinson Pressure Bar, as shown in Figure 1 (c).

The measurement processing was introduced in [15]. The static properties of material mild steel St37 are shown in Table 3.

Since under high-velocity impact events, the thin-walled structures have large plastic deformation or

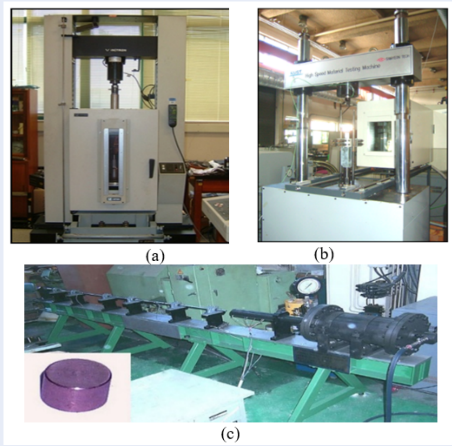

Figure 1: Tensile test with strain rate up to: (a) 0.001 s^{-1}, (b) 100 s^{-1}, (c) 4500 s^{-1}

Table 3: Material properties of mild steel St37 at static test condition.

Material	St37
Young's modulus, E (MPa)	$1.88x10^5$
Yield stress, σ_y (MPa)	186.94
Poisson's ratio, v	0.3
Power law exponent, n	-
Ultimate stress (MPa)	289.56

large strain, thus the effective plastic stress - effective plastic strain characteristics are significant input parameters for simulated process. By conducting series of tensile tests, the true stress – plastic strain with strain hardening exponent are figured out in Figure 3.

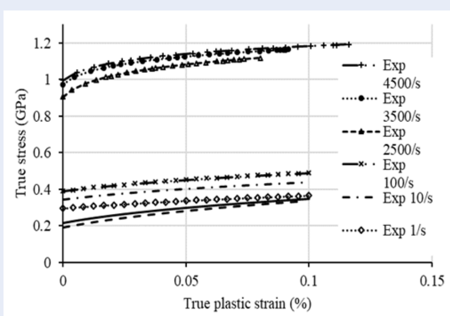

Figure 2: True stress-plastic strain curves at variousstrain rates

The dynamic effect on axial crushing under high impact velocity

The performance on the axial crushing behavior of thin-walled structures subjected to dynamic loads have been introduced by some authors, such as[11,12]. The inertia effect has been seen that a main reason to influence structure's response of thin-walled crash worthiness. According to their publication, due to dynamic plastic buckling, the dynamic progressive folding of crashworthiness structure will occur. Moreover, under different impact velocities, the dynamic corresponding response of structures are not similarly and these publications also indicated that the axial crushing responses of thin-walled structures under dynamic load are better than those in static condition. Furthermore, for material strain rate sensitivity, the impact behaviors of these structure are also affected by strain rate characteristic at high impact velocity. According to N. Jones[11], when the strain rates increase, the yield and ultimate stress of the material increases due to the yield criteria or plastic flow of their material is sensitive to strain rate. One of the main purposes of this paper is to investigate further the effects of strain rate on crushing strength of thin-walled columns subjected to high velocity impact loading.

NUMERICAL MODELING AND SIMULATION

In Figure 3**,** the square column model is simulated with meshing and loading arrangement in finite element method (FEM). The FEM model was studied using four nodes quadrilateral Belytschko-Tsay shell elements and the steel material was modeled by using Mat-Piecewise-Linear-Plasticity type. The strain-rate dependence was included through the Cowper-Symonds coefficients C and q. The dynamic tensile properties at different strain rates were interpolated to construct the constitutive equation of modified Cowper-Symonds model. In this case, eight stress-strain curves in **Figure** 2 were utilizedin numerical simulation.

The numerical models were fixed at one end and the other one is impacted by a rigid wall with a mass of 290 kg at several impact velocities. The square column parameters b, L and t respectively equal 40 mm, 180 mm and 1.5 mm. A friction coefficient of 0.74 was used for the contact between square column and rigid wall to prevent any sliding. To account for the contact between the lobes during deformation of structures, an Automatic-Single-surface contact with friction coefficient equal to 0.57 was specified. The imperfection is needed to ensure that the dynamic progressive

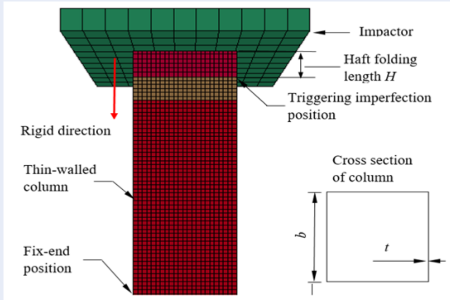

Figure 3: Typical FE models of the thin-walled squarecolumns subjected to axial crushing

buckling of columns is always a local folding. Otherwise, the imperfection was applied to control folding shapes during impact events.

RESULT COMPARISON AND DISCUSSIONS

Instantaneous crushing force P and mean crushing force P_m

The mean crushing forces are obtained from instantaneous crushing fore and it is defined by

$$P_m = \frac{1}{\delta_{tt}} \int_0^{\delta_{tt}} P(\delta) d\delta = \frac{EA}{\delta_{tt}} \quad (5)$$

where: P is crushing force at crushing length δ_o, δ_{tt} is total deformed length and EA is total energy absorption.

Under various high-velocity impact and the effect of strain rate, the crushing behavior of the thin-walled square tubes with respect to the instantaneous crushing force – crushing length and the mean crushing forces – crushing length for strain rate up to 100 s^{-1} and 4500 s^{-1} are shown in Figure 4 and Figure 5 respectively.

As shown in Figure 4 and Figure 5, the instantaneous crushing forces as well as mean crushing forces will increase with increasing load speed from 20 m/s to 50 m/s in both of theoretical and numerical analyses. Otherwise, the group of material includes strain rates with up to 4500 s^{-1} presents higher instantaneous and mean crushing force than those at lower strain rates (up to 100 s^{-1}). That means the structural materials should be stronger at higher rate of loadings. The comparisons in terms of mean crushing forces – crushing length between lower strain rate material and high strain rate material are shown in Figure 6. This figure also points out that at less than 20 m/s of impact velocity, the strain rates effect become insignificantly for crushing response.

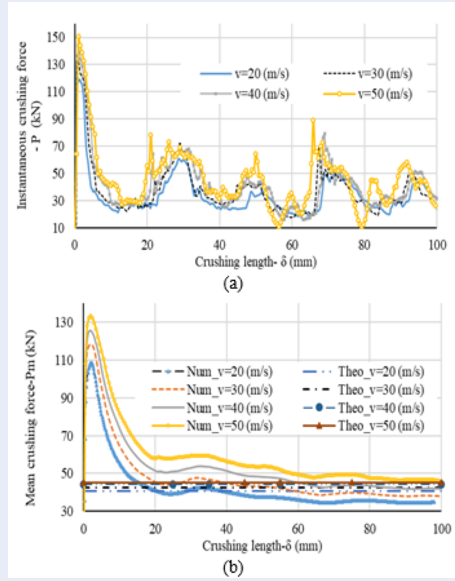

Figure 4: Crushing response with strain rates up to 100 s^{-1} between theoretical analysis and numerical simulation

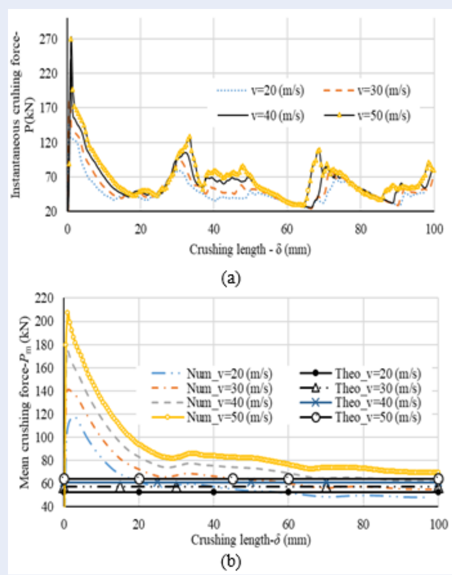

Figure 5: Crushing response with strain rates up to 4500 s^{-1} between theoretical analysis and numerical simulation

Additionally, the compared results in Figure 4 (b) and Figure 5 (b) show a good agreement for mean crushing forces- P_m between theoretical and numerical predictions. The mean crushing forces in numerical simulation are close to those in analytical prediction. It is shown in Table 4.

Table 4: Mean crushing force comparison between numerical and analytical prediction

V (m/s)	Strain rate up to 4500/s		
	Symmetric mode		
	Theoretical	Numerical	Difference
	m (kN)	m (kN)	(%)
20	52.83	53.1	0.5
30	57.31	57.27	0.35
40	61.16	62.27	1.82
50	64.3	69.2	7.66

Total energy absorption (EA) and specific energy absorption (SEA)

The efficiency of energy absorbed structures is well known as a significant design criterion- specific energy absorption (*SEA*) in thin-walled crashworthiness parameters. It can be founded through the total energies (*EA*) which are introduced in Eq. (5). Moreover, during impact events, some parts of the thin-walled structures still undeform, thus considering the crushing length, *SEA* is a ratio defined as *EA* to total deformed mass ($m_{deformed}$) of the structures. They are shown in Figure 6 and Figure 7.

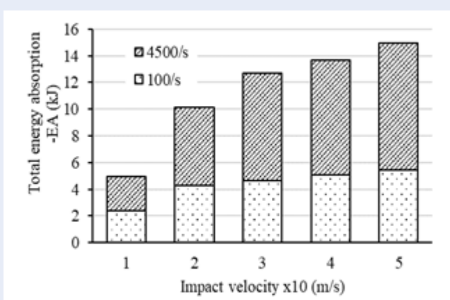

Figure 6: Total energy absorption -EA of mild steel St37 thin-walled columns with strain rate up to100 s^{-1} and 4500 s^{-1}

In Figure 6 and Figure 7, both of total energy absorption and specific energy absorption in 4500 s^{-1} model are higher than those in 100 s^{-1} model at impact velocity from 20 m/s to 50 m/s. Otherwise, by

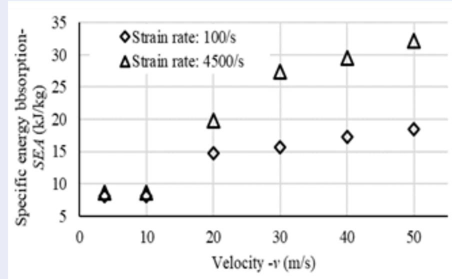

Figure 7: SEA ofmild steel St37 thin-walled columns with strain rate up to 100 $s^{-1}$and 4500 s^{-1}

observing two that figures, the total and specific energy absorption values are repeated in two different strain rate models in impact velocity less than 20 m/s. This attribution of structures shows that the effects of strain rate on axial crushing behavior of thin-walled columns are not significant in velocity less than 20 m/s.

Strain rate versus crushing strength

As shown in section (4.1) and (4.2), it can be seen that better meet in terms of crushing forces and energy absorption capability of high strain rate model compared to low strain rate one. In other words, higher crushing strength of thin-walled columns was founded in structural models which had strain rate value up to 4500 s^{-1} in numerical simulation. Figure 8 and Table 5 compared further this difference.

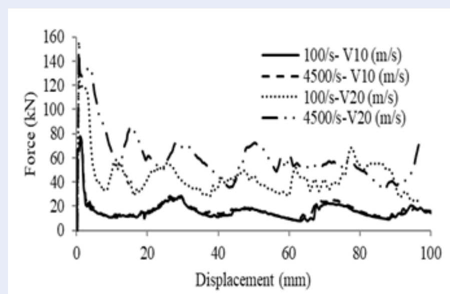

Figure 8: Effect of strain rate on thecrushing response of thin-walled columns (v= 20 m/s)

The results in Table 5 clearly shown strong effects of strain rate as impact velocity increased from 20 m/s to 50 m/s. In detail, at 20 m/s impact velocity, the difference was 19.7% and it increased to 27.8% at 50 m/s impact speed. Indeed, this effect significantly improved the axial crushing resistance of thin-walled columns. Figure 9 will indicate the different folding

Table 5: Crushing strength comparison with in strain rate effects

v (m/s)	Strain rate up to 100/s m (kN)	Strain rate up to 4500/s m (kN)	Difference (%)
20	44.38	53.10	19.7
30	46.46	57.27	23.3
40	50.20	62.27	24.0
50	54.14	69.20	27.8

phenomenon when structure undergoes impact load including strain rate effects at the similar position.

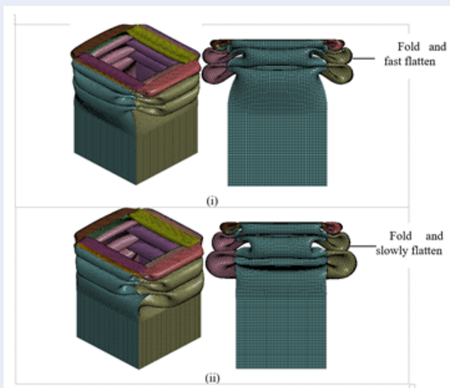

Figure 9: Crushing deformation at v = 30 m/s and t = 3.8second with strain rate (i) 100 s^{-1} and (ii) 4500 s^{-1}

CONCLUSIONS

In this paper, the axial crushing behavior of thin-walled square columns under high impact velocity was investigated through analytical and numerical analysis within the influences of strain rates of materials. The compared results between two groups of materials with strain rates up to 100 s^{-1} and 4500 s^{-1} in terms of crushing forces and energy absorption capability shown that at high strain rates, the thin-walled columns had higher peak forces, mean crushing forces and total energy as well as specific energy absorption than lower strain rates material. The results in theoretical and numerical studies suggested that: for impact velocity less than 20 m/s, the effect of strain rate was not significant but for higher 20 m/s of impact velocity, strain rates influence was very important respect to define the crushing behavior of thin-walled columns structure. Additionally, a good agreement was obtained in terms of mean crushing forces between theoretical and numerical analysis on the condition that material covered strain rates up to 4500 s^{-1} for velocity higher than 20 m/s, as shown in Table 4. For those conditions, the associated Cowper-Symonds coefficients C and q needed to be redefined to deliver more precise results. In other words, it should be use high strain rate for high-velocity impact events.

ACKNOWLEDGEMENTS

We gratefully acknowledge AUN/SEED-Net (Southeast Asia Engineering Education Development Network) for supplying financial, Lightweight Structure Research Group, ITB. The authors also would like to thank to the Computational Solid Mechanics and Design Laboratory – Korea Advance Institute of Science and Technology (CSMD Laboratory – KAIST) for finding the properties of material in static and dynamic conditions. We also express our gratitude to Livemore Software Technology Corporation – LSTC for providing education licenses of program LS-DYNA. Thanks are due to my colleague -Mr. Afdhal for helping to determine the material properties at high strain rate.

AUTHORS' CONTRIBUTIONS

Dr. Hai Tran carried out the experiment, collecting, analyzing experimental data, and writing the manuscript. Prof. Tuan Le-dinh and Msc. Tao. Tran-van shared with me their relevant knowledge. Prof. Leonardo Gunawan, Dr. Sigit. P. Santosa, Dr. Annisa Jusuf, and Prof. Tatacipta Dirgantara guided me throughout my research.

COMPETING INTERESTS

We declare that there is no conflict of whatsoever involved in publishing this research.

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Tạp chí Phát triển Khoa học và Công nghệ – Kỹ thuật và Công nghệ 2025, 8(3):2592-2599

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Bài nghiên cứu

Đặc tính của kết cấu hộp thành mỏng chịu va chạm ở vận tốc cao: Có xem xét sự ảnh hưởng của tốc độ biến dạng

Trần Hải[1,*], Lê Đình Tuân[1], Trần Văn Tạo[1], L. Gunawan[2], SP. Santosa[2], A. Jusuf[2], T. Dirgantara[2]

TÓM TẮT

Bài báo trình bày nghiên cứu ứng xử động học của hộp thép thành mỏng St37 thành mỏng chịu tác động dọc trục với vận tốc cao. Thép mềm St37 là loại vật liệu rất nhạy với tốc độ biến dạng vì mối quan hệ ứng suất-biến dạng của nó phụ thuộc vào tốc độ tải. Trong bài báo này, có cả hai nhóm kết cấu hộp thành mỏng được sử dụng, cụ thể là một nhóm mô hình vật liệu có tốc độ biến dạng lên tới 100 biến dạng/ (nhóm 1) và một còn lại có tốc độ biến dạng lên tới 4500 biến dạng/ (nhóm 2). Nghiên cứu được thực hiện bằng cách sử dụng giải pháp lý thuyết và phân tích phần tử hữu hạn cho tốc độ va chạm 20 m/s, 30 m/s, 40 m/s và 50 m/s. Lực va chạm trung bình và tức thời của kết cấu thành mỏng được dự đoán và so sánh khi xem xét đến ảnh hưởng của tốc độ biến dạng và điều kiện vận tốc va chạm ban đầu. Đối với tốc độ va chạm nhỏ hơn 20 m/s, kết quả cho thấy không có sự khác biệt đáng kể về lực va chạm và khả năng hấp thụ năng lượng của cả vật liệu nhóm 1 và nhóm 2. Tuy nhiên, đối với tốc độ va chạm lớn hơn 20 m/s, mô hình kết cấu hộp thành mỏng nhóm 2 với tốc độ biến dạng lên tới 4500 s-1 cho thấy lực phá hủy, lực cực đại, và khả năng hấp thụ năng lượng cao hơn so với nhóm 1. Do đó, việc phân tích tác động dưới tác động vận tốc cao nên sử dụng mô hình vật liệu có tốc độ biến dạng cao. Hơn nữa, việc so sánh giữa nghiên cứu lý thuyết và nghiên cứu số cũng cho thấy sự phù hợp tốt về mặt lực va chạm trung bình ở các tác động ở các vận tốc cao khác nhau.

Từ khoá: Đặc tính va đập, Chịu va đập, Va chạm, Kết cấu thành mỏng, tốc độ biến dạng

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Lịch sử

- Ngày nhận: 20-09-2023
- Ngày sửa đổi: 09-11-2024
- Ngày chấp nhận: 05-08-2025
- Ngày đăng: 15-08-2025

DOI :

https://doi.org/10.32508/stdjet.v8i3.1206

Trích dẫn bài báo này: Hải T, Đình Tuân L, Văn Tạo T, Gunawan L, Santosa S, Jusuf A, Dirgantara T. **Đặc tính của kết cấu hộp thành mỏng chịu va chạm ở vận tốc cao: Có xem xét sự ảnh hưởng của tốc độ biến dạng**. *Sci. Tech. Dev. J. - Eng. Tech.* 2025; 8(3):2592-2599.