DYNAMIC CRUSHING TESTS OF THIN-WALLED MEMBERS UNDER COMPRESSION

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Abstract
The paper deals with the experimental investigation into crushing collapse behaviour of two types of thin-walled structural members: tubular multi-member element subject to lateral crushing load and top hat-section column under axial compression. Especially designed experimental stand, in which a dynamical crushing load is realized by means of hydraulic system, is presented. Experimental, dynamical load-deformation curves are compared with those obtained from FE simulations and obtained from quasi-static tests. Conclusions concerning an agreement between results of numerical simulations and results of static and dynamic tests are derived.

1. Introduction
Increasing number of impacting events of many types like traffic accidents, collisions of ships or collisions of a ship either with an iceberg or ship grounding on a narrow rock, etc. induced the rapid development of the impact crashworthiness dealing with research into impact engineering problems, particularly in the field of dynamic response of structures in the plastic range and the design of energy absorbers. Since demands of general public of the safe design of components of vehicles, ships, etc. have increased substantially in the last few decades, a new challenge appeared to design special structural members which would dissipate the impact energy in order to limit the deceleration and finally to stop a moveable mass (e.g. vehicle) in a controlled manner. Such a structural member termed energy absorber converts totally or partially the kinetic energy into another form of energy. One of the possible design solutions is the conversion of the kinetic energy of impact into the energy of plastic deformation of a thin-walled metallic structural member.

There are numerous types of energy absorbers of that kind that are cited in the literature [1]. Namely, there are steel drums, thin tubes or multi-corner columns subject to compression, compressed frusta (truncated circular cones), simple struts under compression, sandwich plates or beams (particularly honeycomb cells) and many others. Among the mentioned types the multi-corner columns, namely hat-sections subject to bending and compression are widely used in car doors for side impact protection.

A separate type of the collapsible energy absorber is a system of moderately thin-walled tubes subject to lateral crushing. Such laterally loaded cylindrical clusters have been used in impact attenuation devices of vehicles. They are also employed as crush cushions in roadside safety applications.

A designer of any impact attenuation device must meet two main, sometimes contrary) requirements: The initial collapse load has to be not too high in order to avoid unacceptably high impact velocities of the vehicle. On the other extreme, the main requirement is a possibly highest energy dissipation capacity, which may not be achieved if the collapse load of the impact device is too low. The latter may result in dangerously high occupant “ridedown” decelerations [2].

Thus, the evaluation of the collapse (crushing) behaviour of thin-walled elements becomes an important problem of the modern engineering analysis and concerns particularly dynamic crushing of thin-walled structures. The term “dynamic crushing” is used in the present paper in the sense of progressive crushing of a structure subject to impulse of an applied load. Since any numerical or analytical evaluations of crushing behaviour of thin-walled members are of certain level of approximation, it is an experiment, which plays a crucial part in the analysis.

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2. Subject of investigation

The subject of the present analysis were two types of energy absorbers, namely top hat-section column under compression and a multi-member energy absorber built from circular, cylindrical tubes subject to lateral compressive load. Although the crushing behaviour of two mentioned members is substantially different, however both types of specimens were tested on the same experimental stand and the methodology of experiments (crushing tests) was the same. The aim of the analysis was to verify theoretical solutions, both analytical and numerical obtained under the assumption of static loading and to analyse structural behaviour of the members under investigation subjected to dynamic load.

Different possible configurations of members of the multi-member energy absorber shown in Figure 1. (number of members, thickness of subsequent tubes, their shape, etc.) allow a designer to fulfil the requirements mentioned above. However, the main advantage of an impact attenuation device formed as a single tube or multi-member cluster of laterally crushed tubes is its load-deformation characteristics, i.e. its collapsing stroke approaching even 95% of the tube’s original diameter.

The subject of experimental investigation was initially a single tube [3,6] and then, the three-member tube (Fig. 1,3).

In the second case the subject of investigation was a thin-walled open cross-section profile with edge stiffeners (top-hat section), as shown in Fig. 2, under compression. The profiles were assumed to be pin-joint at both ends and subject to the uniform compression.

3. Preliminary static tests

3.1 Tubular member subject to lateral crushing

The experimental test has been carried out on the model of three-member absorber of equal wall thickness of each tube. Dimensions and material parameters of the tested model are shown in Table 1. The model was manufactured from steel tubes without welding seam. The tubes were spot-welded along their generating lines.

The experiment was conducted on the testing machine Instron of loading range 200 kN. The tested model was subject to compression between two rigid, thick steel plates. The compressive force was applied through the prismatic steel bar. Both compressive force and model deformation (displacement of the upper crosshead beam of the testing machine) was recorded using the integrated, computer aided measurement system of the testing machine. The velocity of loading was relatively low so that the test was of the quasi-static character.

Simultaneously with the experimental test the FE analysis of the tested model was performed. The FE model was loaded in the same manner as the tested specimen, i.e. through the rigid plate completed with the prismatic “inset”. The base of the model was a rigid thick plate. The deformation pattern of the tested model in the initial phase of loading process and the corresponding FE map of equivalent stresses are presented in Fig. 3.

<table>
<thead>
<tr>
<th>Material parameters</th>
<th>Dimensions</th>
</tr>
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<tbody>
<tr>
<td>$\sigma_0 = 335$ MPa</td>
<td>$R_{ext} = 43.75$ mm</td>
</tr>
<tr>
<td>$\sigma_{ult} = 440$ MPa</td>
<td>$t = 5$ mm</td>
</tr>
<tr>
<td>$E = 192000$ MPa</td>
<td>$l = 150$ mm</td>
</tr>
<tr>
<td>$E_t = 1050$ MPa</td>
<td></td>
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</tbody>
</table>
The deformation scenario observed during the test was insignificantly different from the deformation pattern obtained from FE analysis. In the tested model the deformation and yielding of the first member was observed first, secondly the same happened to the last member and finally – to the intermediate, while the theoretical deformation maps indicate the subsequent deformation of the first, second and last member. It was induced by initial imperfections of the tested models on the contrary to the ideal model taken into theoretical calculations.

3.2 Top hat section profile under compression

Preliminary static tests have been carried out on short top-hat section columns subject to uniform compression (Fig.2). The objective of these investigations was to verify the geometrical shape of plastic mechanism of failure taken into the theoretical analysis, both analytical numerical and numerical – using Finite Element Method (FEM). The theoretical solution based on the plastic mechanism approach (yield line analysis) enables one to obtain a quick information about a character of failure and the approximate amount of the energy absorbed by the member, which is useful in the initial phase of the design process of such an absorber [4].

Specimens were made of steel sheets. The dimensions were a = 30, b = 30, w = .8 [mm], wall thickness t=0.6 mm, yield stress \( \sigma_Y = 165 \) MPa. The edge stiffeners were folded on special folding machine. Ends of each column were closed with thin steel plates spot-welded welded to the walls of columns. Each column was loaded through special hinge-ends installed on the testing machine. Regime of tests was the same as for the members described in paragraph 3.1.

Static tests confirmed the shape of the plastic mechanism shown in Fig. 4.

Fig. 4. presents the plastic mechanism formed in the final stage of failure. The failure is initialized by interactive buckling and subsequently – plastic deformation in the flange (Fig. 4c). Typical yield lines were observed in the final stage of failure. However, in the initial stage a local plastic mechanism was formed at the ends of the column, typical rather for closed section columns under axial crushing [2], as shown in Fig. 5.

Special experimental stand has been designed to carry out the dynamic crushing tests of the thin-walled members mentioned above. Dynamic load is realized by means of hydraulic system, the main part of which is the hydro- pneumatic accumulator (1). The hydraulic system enabled to obtain a high crushing force at the relatively high velocity. Both the force and the velocity were controlled. The pump (3) equipped with divider and pressure valve supplies the accumulator. The accumulator (1) is directly connected with the hydraulic servo-motor. The whole energy stored in the accumulator is used to generate a dynamic crushing force exerted on the piston of the servo-motor in a short time and to obtain a high crushing velocity.

Fig. 3. Quasi-static test: a) deformation of the tested model; comparison with FE results., b) – load-deformation diagrams

The comparative diagram of the compressive load in terms of the deflection Uy of the load application point is shown in Fig. 3. Three diagrams obtained from the experiment (quasi-static and dynamic) and from FE static analysis are superimposed here.

The character of both diagrams is similar. The agreement of the values of the initial yield-load is satisfactory. FE element results are slightly overestimated since they concern an ideal theoretical model without any initial imperfections.
4. Dynamic crushing tests

The tested specimen is installed between plates (5). The design enables to obtain a simple (hinge) support of both ends of the tests section in the case of hat-section column, which is shown on the left side of Fig. 6. The displacement (deflection) of a specimen is measured with the linear potentiometer transducer (7), while the crushing force is measured with the strain gauge transducer (8). Both sensors (7) and (8) are connected with the strain gauge bridge controlled by the computer PC. The crushing force versus the specimen’s deflection is recorded in this way.

Fig. 5. Load – shortening diagram of top hat-section (quasi-static test).

Fig. 6. Crushing test experimental stand
The average value of crushing velocity obtained by the pneumo-hydraulic system was about 12 m/s [43,2 km/h]. Dynamic tests on both types of specimens described above were carried out on the stand.

4.1 Tubular member subject to lateral crushing

Failure modes of absorbers subject to dynamic load were similar to that observed under the static load (Fig. 7) and also similar to the deformation pattern obtained from FE static analysis. However, load-deformation diagrams were different from those obtained in static tests, as it is shown in Fig. 8 and 9. Initial failure load corresponding to the first yield was about 20-26% higher than that observed in static tests and obtained from FE static analysis. Mainly, it is caused by the increase of yield point under dynamic load, which is strongly dependent on the strain-rate [2,5]. Nevertheless, character of dynamic experimental loading paths was similar to those obtained from FE static analysis. Thus, FE static analysis can be used to an estimation of the initial failure load and energy dissipated by the absorber. It is important, because FE dynamic “implicit” analysis is extremely time consuming.

Fig. 7. Comparison of failure patterns of tubular absorbers subject to dynamic crushing (absorbers 1-5), static crushing (absorber 6) and FE static analysis results

Fig. 8. Load-deflection diagrams of tubular absorbers. Comparison of dynamic and quasi-static tests

Fig. 9. Load-deflection diagrams of tubular absorbers. Comparison of dynamic tests and static FE analysis

Fig. 10. Failure mechanisms of top hat-sections under compression: a) dynamic crushing, b) quasi-static crushing
4.2. Top hat-section under compression

Failure mode observed during dynamic crushing tests was in this case different from the failure mechanism reported at static load (Fig. 10). While static failure was initialized by local plastic deformation at the ends of the column (Fig. 10b), in the contrary during dynamic crushing the failure mechanism was formed at the centre of the column (Fig. 10a). Comparison of dynamic and static loading paths is shown in Fig. 11. Ultimate crushing load was significantly higher than the static one. Generally, the dynamic crushing load path ordinates were about 50% higher than those of the static load-deformation path.

![Graph](image)

**Fig. 11. Comparison of static and dynamic load-deformation diagrams of top hat-section column under compression**

5. Final remarks

Ultimate crushing load of the thin-walled structural element is 20-50% higher than the static maximum load. It results in an increase of the energy absorbed during crushing process. Response of the structure to the dynamic load is of similar character as to the static one in the case of tubular absorber, but significantly different in the case of top hat-section column. Particularly failure modes under static and dynamic crushing load differ significantly in the latter case. In both cases load-deformation diagrams obtained from dynamic crushing tests display “fluctuations” around static load paths, which are induced by vibrations of tested specimens and also of elements of the experimental stand. Results of experiments are extremely sensitive to initial imperfections.

Static or quasi-static numerical analysis gives an approximate answer about a quantitative character of the failure dynamic loading path of a thin-walled structure. It should be underlined here, that analytical and numerical analysis of both members under consideration was of preliminary character and the research is currently continued into the evaluation of strain-rate sensitivity analysis (both FE and based on the yield line approach [5, 7]). Results of an analysis taking into account the strain-rate will be probably closer to the results of dynamic crushing tests.

**References**


