

PREDICTION OF CRUSHING BEHAVIOUR OF HONEYCOMB STRUCTURES

A Chawla¹, S Mukherjee¹, Dileep Kumar², T. Nakatani³ and M. Ueno³

¹ Dept of Mechanical Engineering
Indian Institute of Technology
New Delhi 110 016

² Terminal Ballistics Research Laboratory
Chandigarh, India

³ Japan Automobile Research Institute
Tsukuba, Japan

ABSTRACT A finite element methodology has been developed for predicting the behaviour of honeycomb structures. Dynamic analysis of hexagonal aluminium honeycomb structures is carried out using PAM-CRASHTM, an explicit FE analysis code, and the result are verified against experimental data. Relationship between the crushing behaviour of honeycomb and simulation parameters has been established. The simulation results are also compared with theoretically predicted values.

Keywords: Finite Element Modelling, Impact, Dynamic modelling, Honeycomb structures, Crushing Behaviour.

Nomenclature:

F_n	Normal Force	$\sigma_{0.2}$	0.2% proof stress
F_s	Shear force	σ_u	Ultimate stress
U_n	Ultimate tensile strength in the failure model	S_{crush}	Crush strength
U_s	Ultimate shear strength in failure models	S_{comp}	Compressive strength
A_1, A_2	Constant used in rupture model	H	Fold thickness
E'	Elastic modulus of the base material	E_s	Young's modulus obtained from Simulations
E	Equivalent elastic modulus in the axial direction	E_a	Young's modulus obtained from analysis
t	Foil thickness	S_{cr_a}	Crush strength obtained from analysis
θ	Cell angle	S_{cr_s}	Crush strength obtained from simulations
S_o	Flow stress	S_{co_a}	Compressive strength obtained from analysis
D	Cell size	S_{co_s}	Compressive strength obtained from simulations

INTRODUCTION

Aluminium honeycomb is a structure made up of hexagonal aluminium foil cells (Figure 1). It derives its name from its close resemblance to a bee honeycomb, though there is no variation in the depth direction. The honeycombs of hexagonal cell structure are characterised by considerable rigidity in shear, high crushing stress, almost constant crushing force, long stroke, low weight and relative insensitivity to local loss of stability.

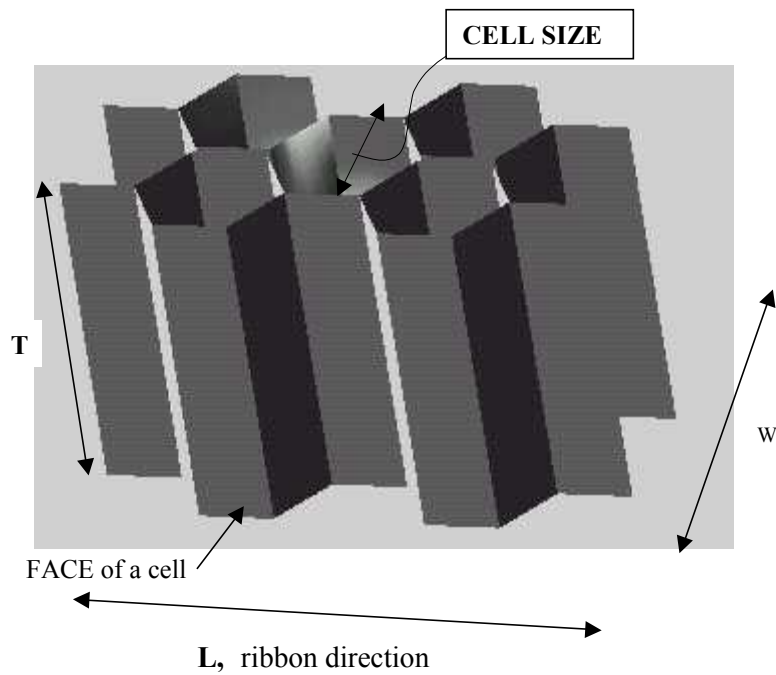


Figure 1, The nomenclature of the honeycomb.

Initial models developed to predict the approximate crushing stress of hexagonal cell structures subjected to axial loading were semi-empirical [1]. Energy based analytical method, in conjunction with a plastic flow minimum principle for determining the crushing strength are more accurate [2].

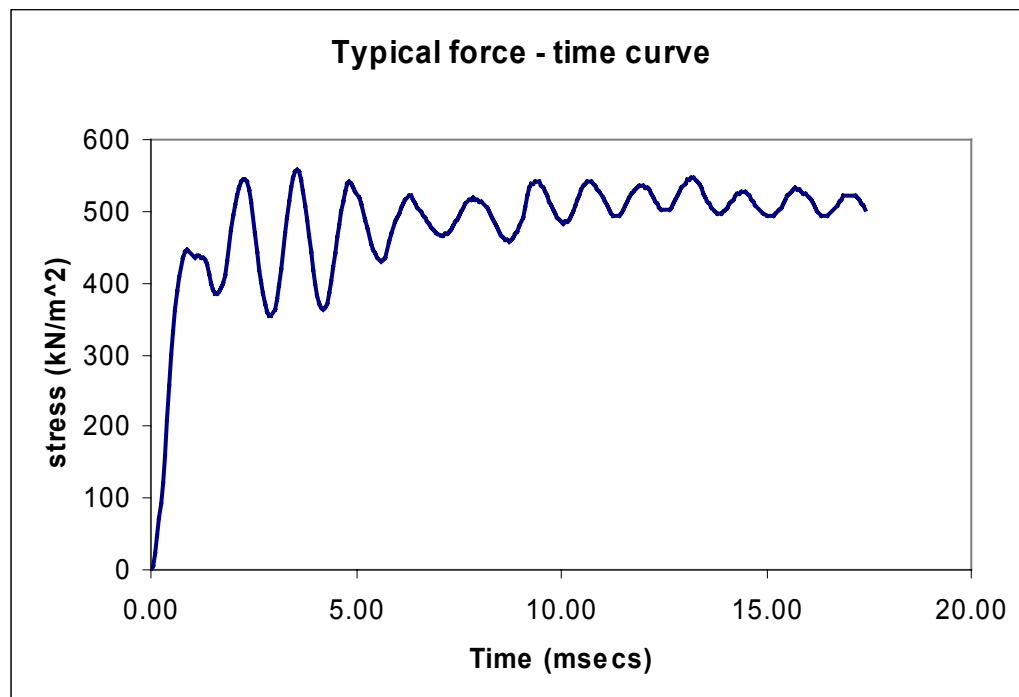


Figure 2: A typical load – time behaviour of a honeycomb block under crush.

Earlier experimental results indicate that when honeycomb specimen are loaded quasi-statically, they exhibit a sharply rising peak load, followed by a series of oscillatory crush

loads with a nearly constant mean value [3]. In the dynamic experimental curve we obtained, shown in Figure 2, the initial peak load is not seen because the data was not sampled at fast enough rates. The oscillations correspond to the onset of the progressive plastic buckling and subsequent plastic folding of the cellular structures. Manufacturer specifications of honeycombs label the overshoot peak as the 'bare compressive strength' and the plateau region as the 'crush strength' on the stress-strain curve. The crush strength of a honeycomb structure is directly related to its energy absorbing capability. The average dynamic crush strength is in the range of 1.33 to 1.74 times that obtained under quasi-static loading conditions [3]. This increase can be attributed to more complicated and compacted plastic folding mechanisms during dynamic loading, the inertial effect and the strain-rate effect. The crush strength was also found to vary with the striking velocity of the impactor. Experimental demonstration of strain-rate dependence through stress-deformation curves and the energy-absorption characteristics of metal honeycombs at varying initial strain rates upto 2000/sec are available [4]. The collapse for the aluminium honeycomb is seen to initiate at only one of the surfaces, and then propagates uniformly along the length.

Analytical results are available for quasi-static loading. The behaviour of honeycomb structures under dynamic loading had only been studied experimentally. In this paper, results of FE simulation of the dynamic crush of honeycomb structures are presented. The results are consistent with experimental measurements. This method hence could be a useful tool for design of honeycomb structures to meet specific design requirements.

To generate the FE model, aluminium honeycomb structures have been modelled using IDEASTM, and the dynamic analysis has been carried out using PAMCRASHTM. The largest element size that yields reasonable accuracy has been established to economise on computer run time. Two alternate approaches to model the adhesive bonding between shell faces have been studied. The observed effects of varying the impactor velocity and material properties in the FE simulations are consistent with experimental results. A comparison of the simulation results with available experimental results and analytical models is presented.

FINITE ELEMENT MODELLING

Aluminium honeycomb structures made from $\frac{3}{4}$ -Al-5052-0.003N and $\frac{3}{4}$ -Al-5052-0.002N have been studied. The geometrical model was developed using I-DEASTM master modeller and meshed using thin shell elements. The finite element mesh was then ported to PAM-GENERISTM to set boundary conditions. The numerical solutions are carried out using the explicit finite element code PAM-CRASHTM. The post-processor PAM-VIEWTM was used for visualisation. The honeycomb structure had a length of 109.7 mm (along ribbon direction), width of 76.7 mm and thickness 100 mm to mimic the specimens used for experimentation. The density of $\frac{3}{4}$ -Al-5052-0.003N honeycomb was 27.77 kg / m³ and for $\frac{3}{4}$ -Al-5052-0.002N, 18.51 kg / m³.

The resulting structure had 18 complete hexagonal cells. A rigid wall was defined at the bottom of the honeycomb structure. The impactor, modelled as a rigid body, as it is significantly stiffer than the honeycomb, strikes the honeycomb at the top end.

Post impact, due to deformation, segments not originally proximal may interact with each other. Three types of contact interface are used to model this phenomenon in the simulations. Conventional master-slave contact is used between impactor and honeycomb. Defining self-

contact over the honeycomb walls inhibits interpenetration between the folds in the honeycomb cells during progressive formation of plastic folds. To model the adhesive bond, tied contact between nodes on adjacent faces on different honeycomb cells are used. Tied contacts allow elements to move apart after force limits are exceeded, but inhibit penetration.

The honeycomb was fabricated from 5052-H39 grade Aluminium, for which relevant material properties could not be found in literature. It is however known that their ultimate tensile strengths are generally higher than those of H38 materials by at least 10 MPa [5]. The material properties used in our simulations are Young's modulus = 70GPa, initial Yield stress = 265 MPa, Poisson's ratio = 0.33, Density = 2680 kg/m³. The constitutive behaviour of the thin shell element is assumed to be elastic-plastic with Von-Mises's isotropic plasticity algorithm being applicable. The transverse shear effect and plastic hardening is included in the material model. This type of material model is referred to as material type 103 in PAM-CRASHTM [6]. The tangent modulus was taken to be 0.5718GPa at 300MPa stress.

PARAMETRIC STUDIES IN SIMULATION

Effect of element size

Varying the number of elements for a fixed geometry leads to variation in element size. It is important to establish the mesh size that optimises simulation time without significant penalty on accuracy. The $\frac{3}{4}$ -Al-5052-0.003N model was selected for this study. Simulations were run with variation in the number of elements in ribbon as well as cell width directions. From the simulation, rigid-wall forces vs. time and impactor displacement vs. time, plots were extracted. Effective stress is calculated as force divided by total cross-section area of the structure and effective strain as displacement of C.G. of impactor divided by honeycomb thickness. The stress vs strain diagram is plotted for each mesh type.

The nomenclature used to describe the models is that 3x30 is to be interpreted as 3 elements along thickness direction and 30 elements along ribbon direction for each face of honeycomb cell. It was concluded that for small geometric size of structure, FE model of 6x80 elements per cell gives good result whereas for large size of problem 6x60 elements may be used without introducing large errors. Figure 3 below shows the variation in stresses with different mesh sizes for a typical case.

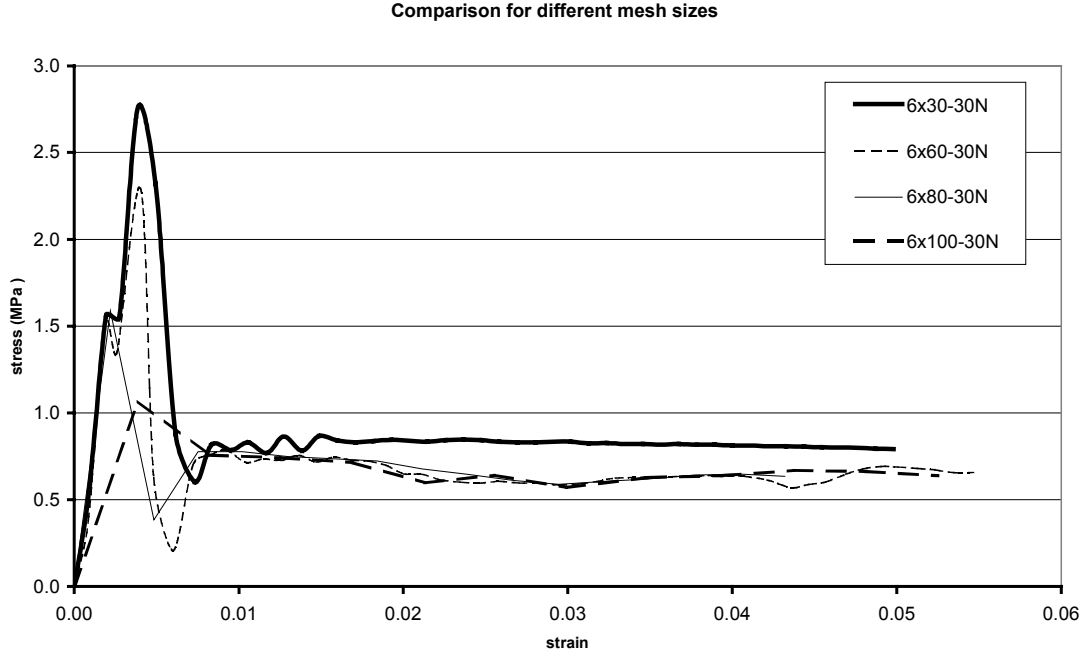


Figure 3 Effects of number of Elements on crushing behaviour

Simulation of adhesive bonding

During fabrication, adjacent sides of hexagonal cells of aluminium honeycomb structure are glued together. Two approaches were used to simulate the adhesive bonding between the adjacent sides.

1. The nodes of the adjacent element of adjoining faces were merged in IDEASTM and then transferred to PAM-GENERISTM in universal file format
2. The FE model was transferred from IDEASTM to PAM-GENERISTM without merging the nodes and then a tied contact interface was defined between the adjoining elements and nodes.

The tied contact is initiated at the start of the simulation and does not allow any relative motion of the slave and master nodes until rupture. The rupture failure criterion based on normal and tangential forces is defined as [6]

$$\left(\frac{F_n}{U_n} \right)^{A1} + \left(\frac{F_s}{U_s} \right)^{A2} \leq 1.0 \quad [1]$$

From the technical data sheet of the manufacturer, U_n and U_s for epoxy adhesive (F21036 & F21036-AF) are 4.47 and 29.3 Mpa respectively. The exponential components $A1$ and $A2$ may be taken as $A1 = A2 = 2$ [7]. Results of the simulation of $\frac{3}{4}$ -Al-5052-0.003N with 6x60 meshing using the two approaches for modelling the adhesive are plotted in Figure 4.

The model with merged nodes shows significantly higher compressive strength compared to model with glued nodes. This is expected, as the merged nodes would result in greater stiffening of the model. The variation in crush strength is only about 5%. The CPU time

needed to solve the glued model is about 2.5 to 3 times more than the merged nodes model. We could conclude that the optimum solution of honeycomb crush simulations might be obtained with merged nodes model in reasonable CPU time and the results scaled down later to account for the glued model. The simulations discussed subsequently in this paper are all with the merged nodes model.

Effect of variation in impactor velocity

The effect of impactor velocity on the honeycomb crush behaviour was also studied in simulation. The model used was $\frac{3}{4}$ -AL-5052-0.003N with 6x60 meshing. Three simulations were carried out with initial velocities of impactor as 2.778 m/sec, 5.496 m/sec and 9.722 m/sec that correspond to different drop heights. The stress-strain curves for all three cases are plotted in Figure5. We observe that the compressive strength of the honeycomb structure increases substantially with increase in impactor velocities. The crush strength, which is the gross structural behaviour, is almost invariant in this regime of impactor velocity change. This is in consonance with the experimental observation [8] that crushing strength does not change significantly for impact velocities of 2 to 28 m/sec.

Choice of material model

Studies on the dynamic plastic behaviour of different structures show that the energy consumed in the plastic deformation dominates the elastic energy [9]. So rigid-plastic material models that neglects the elastic effects also give reasonable result in analysis. This phenomenon was investigated for the crushing behaviour of aluminium honeycomb structure in simulation by using different material model. The results from use of bilinear elastic-plastic and bilinear elastic-perfectly-plastic material models are plotted in Figure6. The plots show that the compressive strength is nearly identical for the two cases. However the elastic perfectly plastic material model shows comparatively lower crush strength at large strains. From this result, it may be concluded that the compressive strength depends only on the yield strength of the basic material.

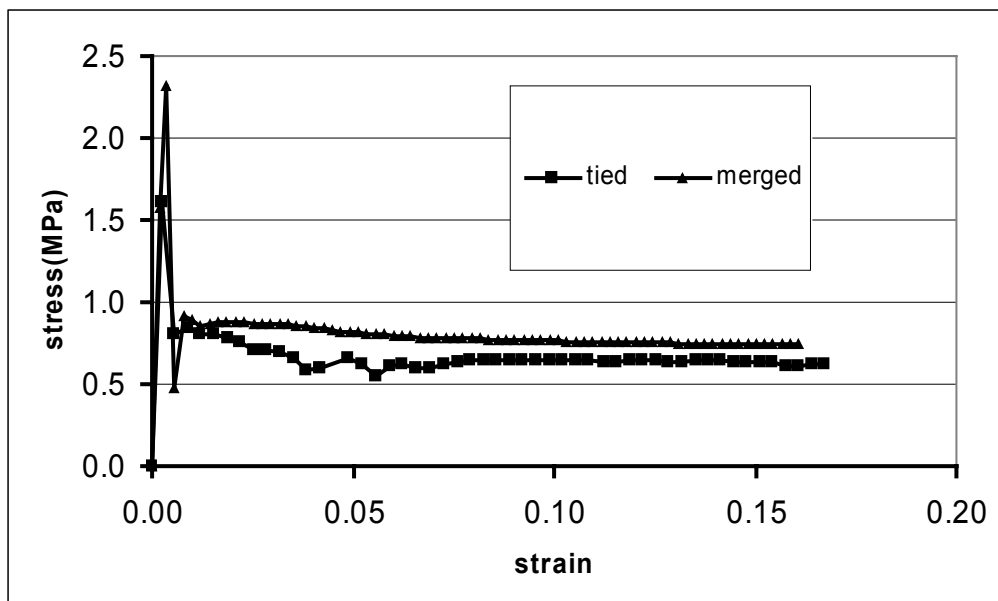


Figure 4: Effects of Glued vs. Merged Nodes on Crushing Behaviour

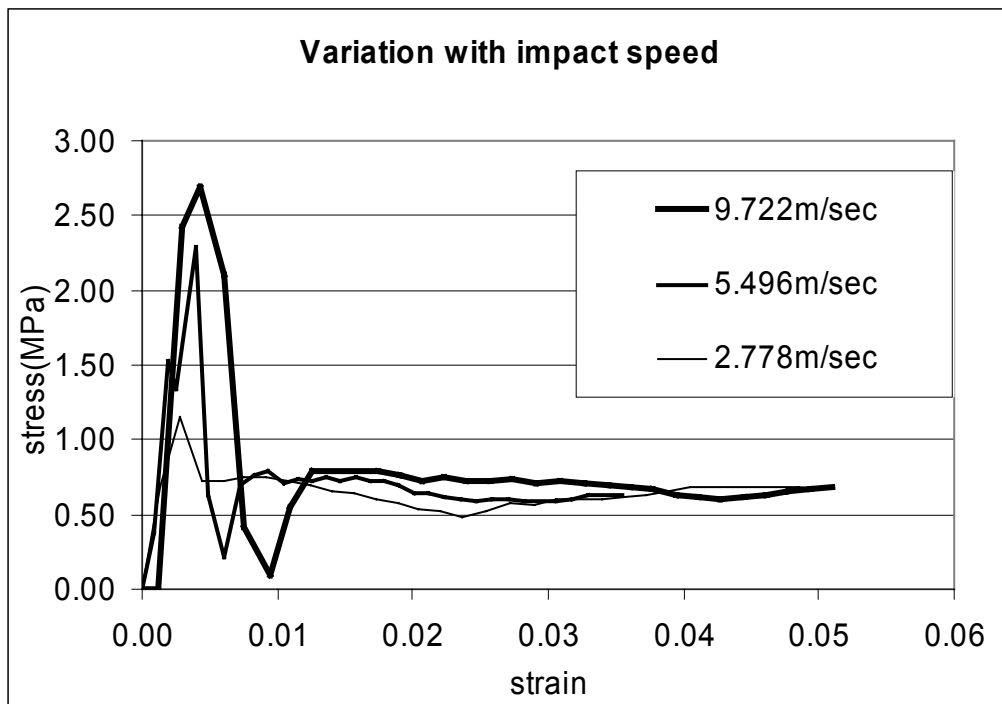


Figure 5: Effects of Impactor velocity on crushing behaviour

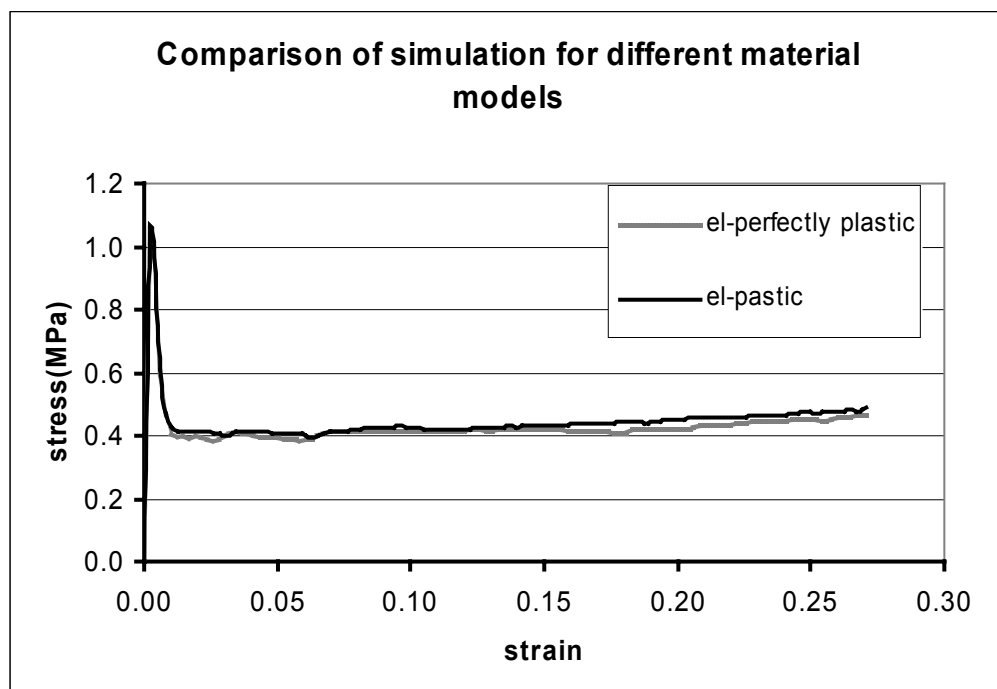


Figure 6: Effects of Material Models

EXPERIMENTAL VALIDATION

This section compares results of dynamic simulation and the experimentally measured values of stress and strain. Dynamic test was conducted by dropping an impactor of mass 137 kg from a height of 1.54 meter on the honeycomb block. The drop height corresponds to a striking speed of 5.496m/sec. Controlling the impactor motion through guide ways ensured that the top edge of the honeycomb was in full contact with the impactor. The data was sampled at 20KHz and processed to obtain the stress-strain curve. Figure 7 shows the drop test set up at the Japan Automobile Research Institute, Tsukuba, Japan, which was used in these experiments. Figure 8 and Figure 9 shows the experimental stress vs strain plots superposed with FE results.

The simulations show the peak strength, though they are missing in the experiment. In simulation, the peak overshoot was recorded at about 5×10^{-5} seconds. Hence, to get the compressive strength from dynamic experiments the sampling rate has to be increased at least by 4 times i.e. sampling rate should be of the order of 80KHz. The crush strength in simulation was also at variance, about 30% higher than the experimental value. The variation can be attributed to the following effects.

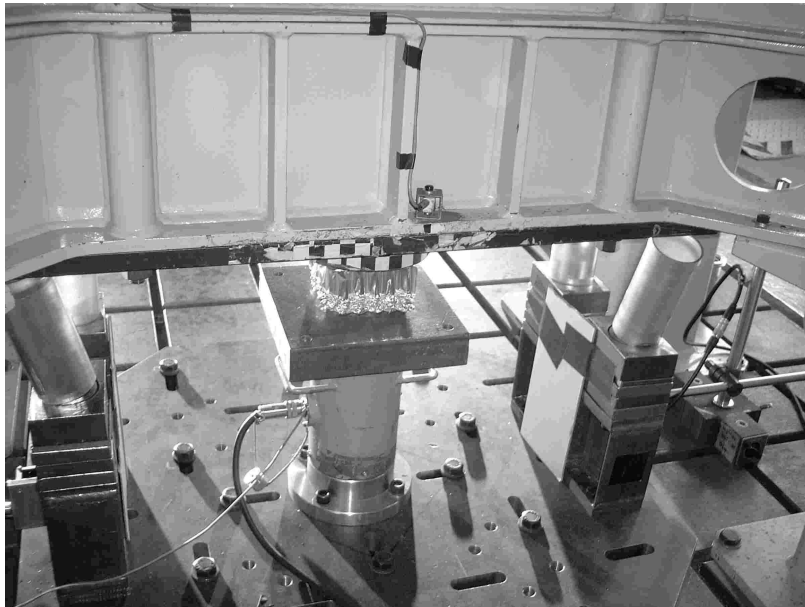


Figure 7: The test setup used.

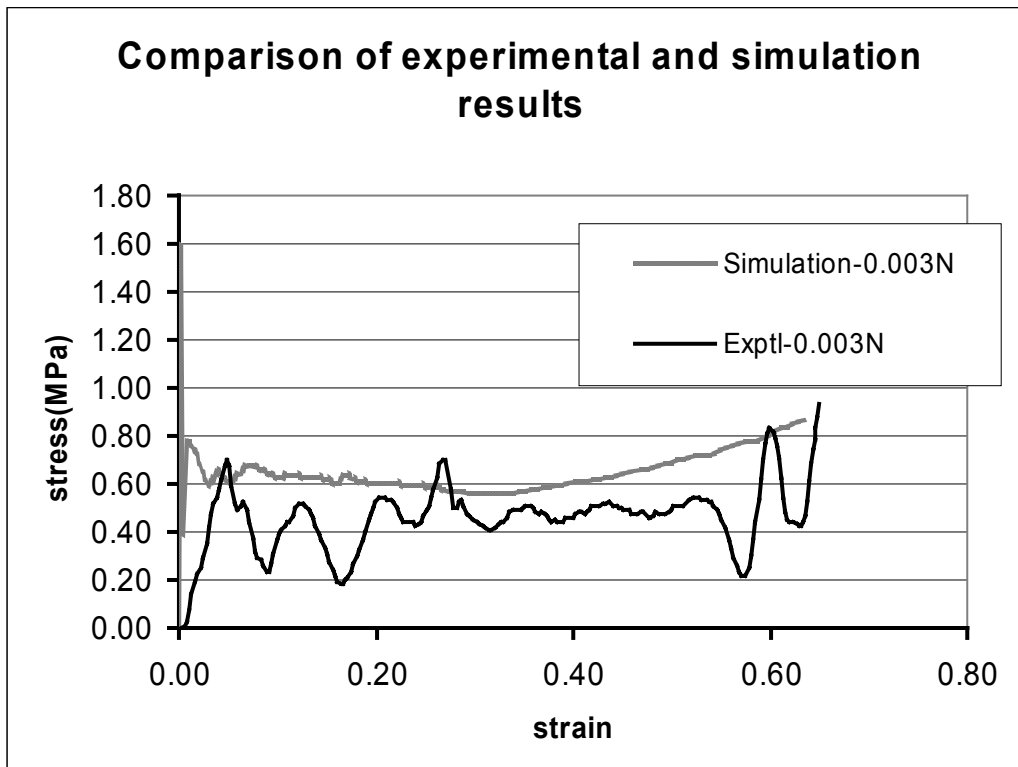


Figure 8: Comparison of Results $\frac{3}{4}$ -Al-5052-0.003N Honeycomb

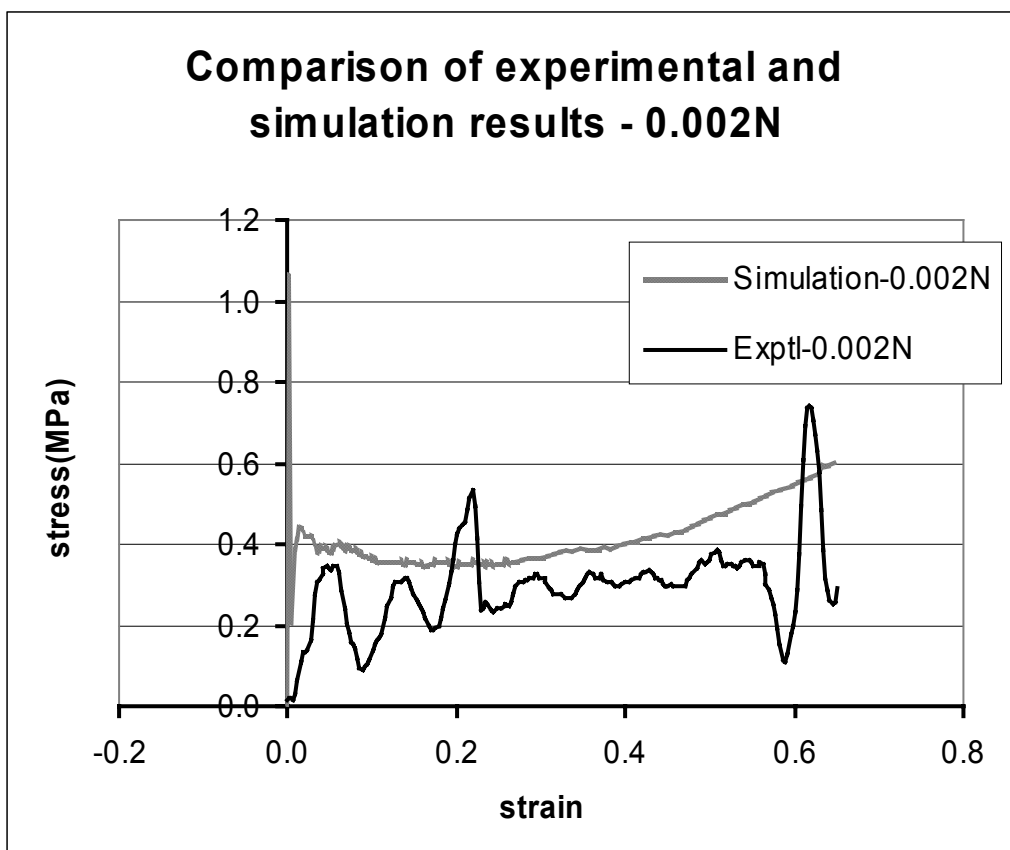


Figure 9: Comparison of Results $\frac{3}{4}$ -Al-5052-0.002N Honeycomb

1. The material properties of Aluminium 5052-H39, which are used in manufacturing the honeycombs, were not available in literature. The variations in the actual material properties of test specimen and simulation model may be one of the reasons for discrepancies in results.
2. The faces of honeycomb cells are perforated with pinholes to allow the trapped air to come out during compression. The entrapped air, if any, may effect the crushing properties of the honeycomb. Since we have not modelled the gas entrapment, modelling the pinholes may not be significant. Purely from a structural mechanics perspective, the pinholes modify the section properties as well, though by a small amount which we have ignored for now.
3. Geometrical imperfections, like irregularities in the hexagonal shapes of honeycomb may be introduced during the fabrication of honeycombs test specimen.
4. In experimentation, there may be broken cells around the periphery of the cross-sectional area of specimen. It had been observed that the crush strengths of published manufacturer's test data are lower by 20-30% compared to their experimental result with the carefully prepared specimen without broken cells on the specimen periphery [3].

COMPARISION WITH THEORETICAL RESULTS

Analytically, equivalent axial Young's modulus for the honeycomb is given by the following experimentally validated relation [10].

$$E = [t * E' (1 + 2 \cos \theta)] / (2D * \sin \theta (\cos \theta + 1)) \quad [2]$$

Analytically the crush strength for static loading of multiple honeycomb cells is given as follows [2].

$$S_{\text{crush}} = 16.56 S_o (t/D)^{5/3} \quad [3]$$

A key assumption here is that the half-length of buckling wave, H and the width of the element during the deformation process are constant. The, half fold thickness is given by,

$$H = 0.821 (t D^2)^{1/3} \quad [4]$$

Where S_o , may be taken as $(\sigma_{0.2} + (\sigma_u)/2)$ [11]. These theories, however, are derived for quasi-static loading of the honeycomb.

The modulus of elasticity, compressive strength and fold thickness for $\frac{3}{4}$ - AL-5052-0.003N and $\frac{3}{4}$ - AL-5052-0.002N models have been calculated using the Equations 2, 3 and 4 above, and compared with the simulation results in Table 1. The simulations are for dynamic loading. Experimental data is for dynamic test. The manufacturers data, taken from the product catalogue is from quasi-static tests.

In honeycomb related literature, conventionally, variation between values has been expressed as ratio instead of percentages. The ratio of simulation to analytical values of modulus of elasticity is in the range of 1.9 to 2.1. The ratio for crush strength is 1.5 to 1.7. These figures can be interpreted as the ratio between dynamic and static values for the honeycomb, which

match with the range reported in literature [4]. The average dynamic crush strength has been reported to be about 1.33-1.74 times that under quasi-static loading condition [3]. The FE simulation is seen to be a better estimator of the crush strength than analytical formulation currently available.

The ratio of compressive strength to crush strength is found in the range of 2.5 –3.1 in simulation. This matches with the range of 2.3 to 2.8 reported in previous work [3].

In progressive plastic buckling range, the peaks in the stress-strain curve obtained in simulation, corresponding to the lobe formation, are not very prominent and are of smaller size. The quasi-static loading tests give more distinct peaks as the energy required is more compared to dynamic tests. This is reflected in the simulation carried out by us.

TABLE 1 Comparison of Results from simulation, analysis, experiment and catalog

Model	Analytical (static) [a]	Simulation (dynamic) [s]	Experiment Data [e]	Manufacturer Data (static) [m]	Ratio
SHOWA ¾ - AL-5052- 0.003N	E=0.37Gpa S _{crush} = 0.47MPa 2H= 4.96mm	E=0.726GPa S _{crush} =0.607Mpa S _{comp} =1.59 MPa 2H= 3.30mm	S _{crush} = 0.5 MPa	S _{comp} = 0.69 MPa (From Showa data sheet)	E _s /E _a = 1.94 S _{crush_s} /S _{crush_a} = 1.29 S _{crush_e} /S _{crush_a} = 1.06 H _s /H _a =0.664
					S _{comp_s} /S _{comp_m} =2.30
SHOWA ¾ - AL-5052- 0.002N	E=0.25Gpa S _{crush} =0.24Mpa 2H= 4.33mm	E=0.48 GPa S _{crush} =0.36Mpa S _{comp} = 1.06MPa 2H= 3.28mm	S _{crush} = 0.3 MPa		E _s /E _a = 1.94 S _{crush_s} /S _{crush_a} =1.5 S _{crush_e} /S _{crush_a} = 1.25 H _s /H _a = 0.756

CONCLUSIONS:

FE simulations of dynamic crushing of honeycomb structures have been presented. The crushing strength of a honeycomb structure is known to depend on its geometry and on the material property. In FE simulations, the size of the FE mesh is also seen to affect the results substantially. The optimal FE mesh size has been established by refining the mesh till convergence is observed.

The FE models reproduce the experimentally observed effect of the foil thickness and the cell size on the crushing strength of honeycomb structures. The adhesive bonding between cell faces were simulated by two different approaches, using glued nodes and using merged nodes. The merged-nodes model gives reasonably good results with substantially lower simulation time. FE models also predict that an increase in impactor velocity increases the compressive strength of honeycomb but does not significantly alter the crushing strength.

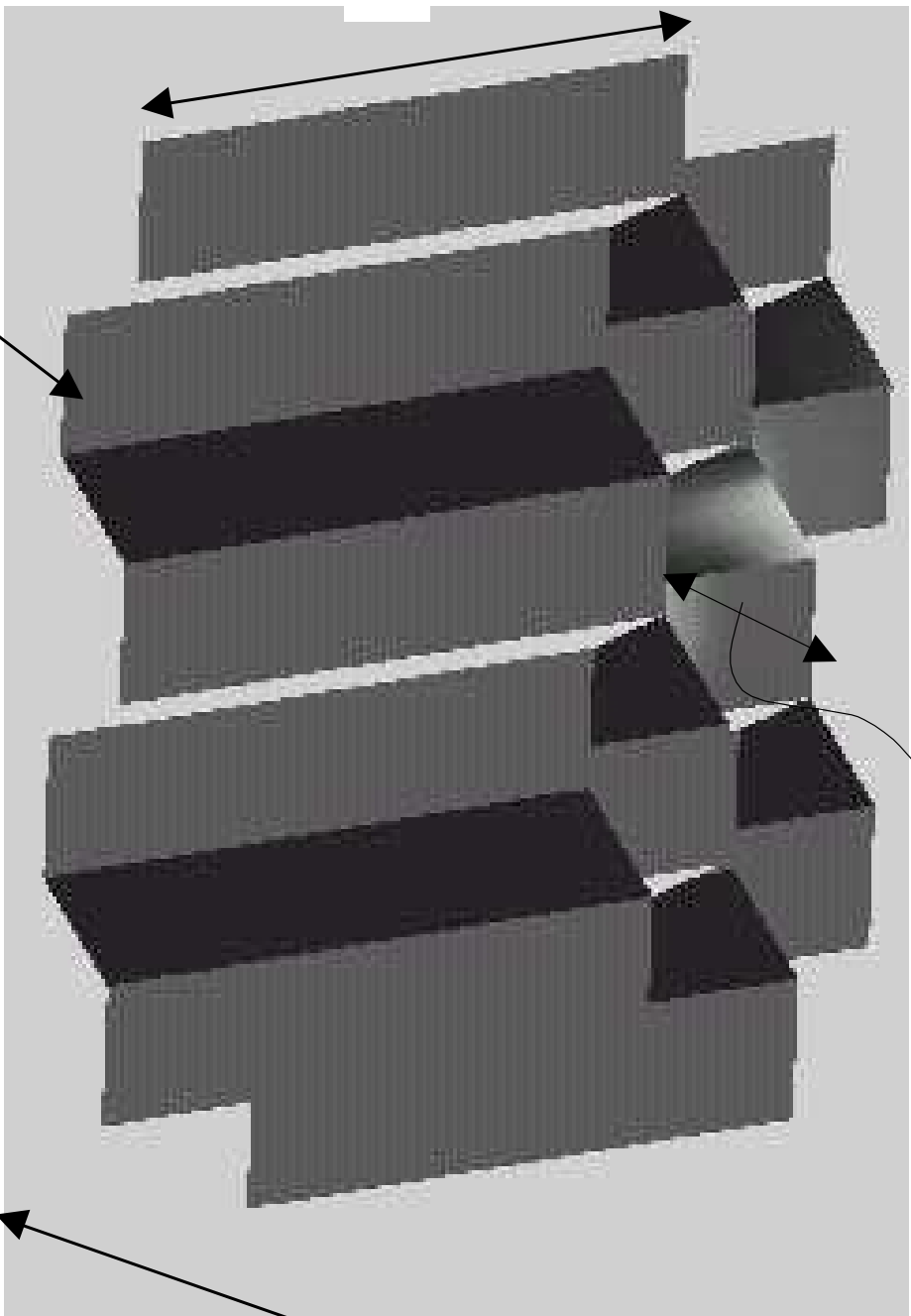
The simulation results are compared with analytical results of quasi-static loading and with data from the manufacturer. The ratio between simulated and analytical strength values is almost constant for different honeycombs considered. This corresponds to the ratio of the strengths between dynamic and static loading conditions and is within the range reported earlier. The simulation results were also compared with experimental results. The probable causes of discrepancies have been enumerated.

The methodology demonstrated to model the honeycomb can be used to study the effect of other parameters like overall size, cell size, foil thickness, thickness of honeycomb, number of complete cells and material properties. Manufacturers can carry out such sensitivity analysis to design honeycombs to fit specific performance corridors, reducing trials.

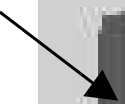
REFERENCES

1. McFarland R. K. Jr., "Hexagonal Cell Structures Under Post-Buckling Axial Load", *AIAA Journal*, 1963, **1**(6), 1380-1385.
2. Wierzbicki Tomasz, "Crushing Analysis Of Metal Honeycombs", *Int. J. Impact Engg*, 1983 **1**(2), 155-174.
3. Wu Enboa and Jiang Wu-Shung, "Axial Crush Of Metal Honeycombs", *Int. J. Impact Engng*, 1997, **19**(5-6), 439-456.
4. Baker W. E., Togami T. C. and Weydert J. C. [1998] "Static And Dynamic Properties Of High-Density Metal Honeycombs", *Int. J. Impact Engg*, 1998, **21**(3), 149-163
5. Corden John, *Honeycomb Structure - Engineering Materials Handbook*, ASM International, 1990 721-728.
6. ESI Group, *PAM-CRASH User Manual*, ESI Group Software Product Co. Paris, 2000.
7. Santosa S. and Wierzbicki T. "Crash Behavior Of Box Columns Filled with Aluminium Honeycomb or Foam", *Computers And Structures*, 1998, **68**, 343-367.
8. Zhao Han and Gary G, "Crushing Behaviour of Aluminium Honeycombs Under Impact Loading", *Int. J. Impact Engg*, **21**(10), 827-836.
9. Jones Norman [1989] *Structural Impact*, Cambridge University Press, Cambridge, 1989.
10. Meraghni F., Desrumaux F. and Benzeggagh M. L., "Mech Behaviour Of Cellular Core For Structural Sandwich Panels"— *Composites: Part A* 30, 767-779.
11. Langseth M. and Hopperstad O. S., Static and Dynamic Axial Crushing Of Square Thin-Walled Aluminum Extrusions, *Int. J. Impact Engg*, 1996, **18**(7-8), 949-968.

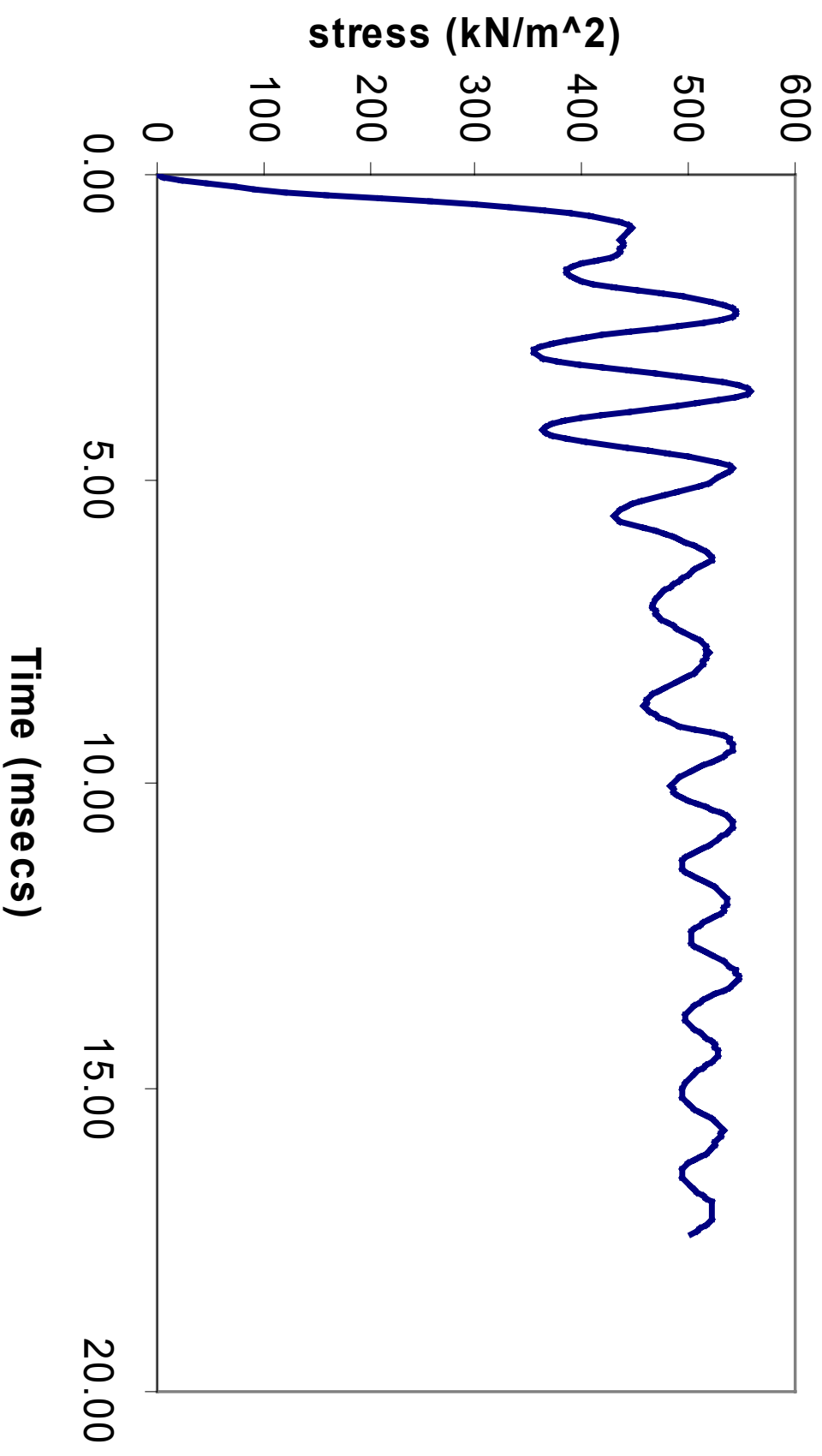
CELL SIZE



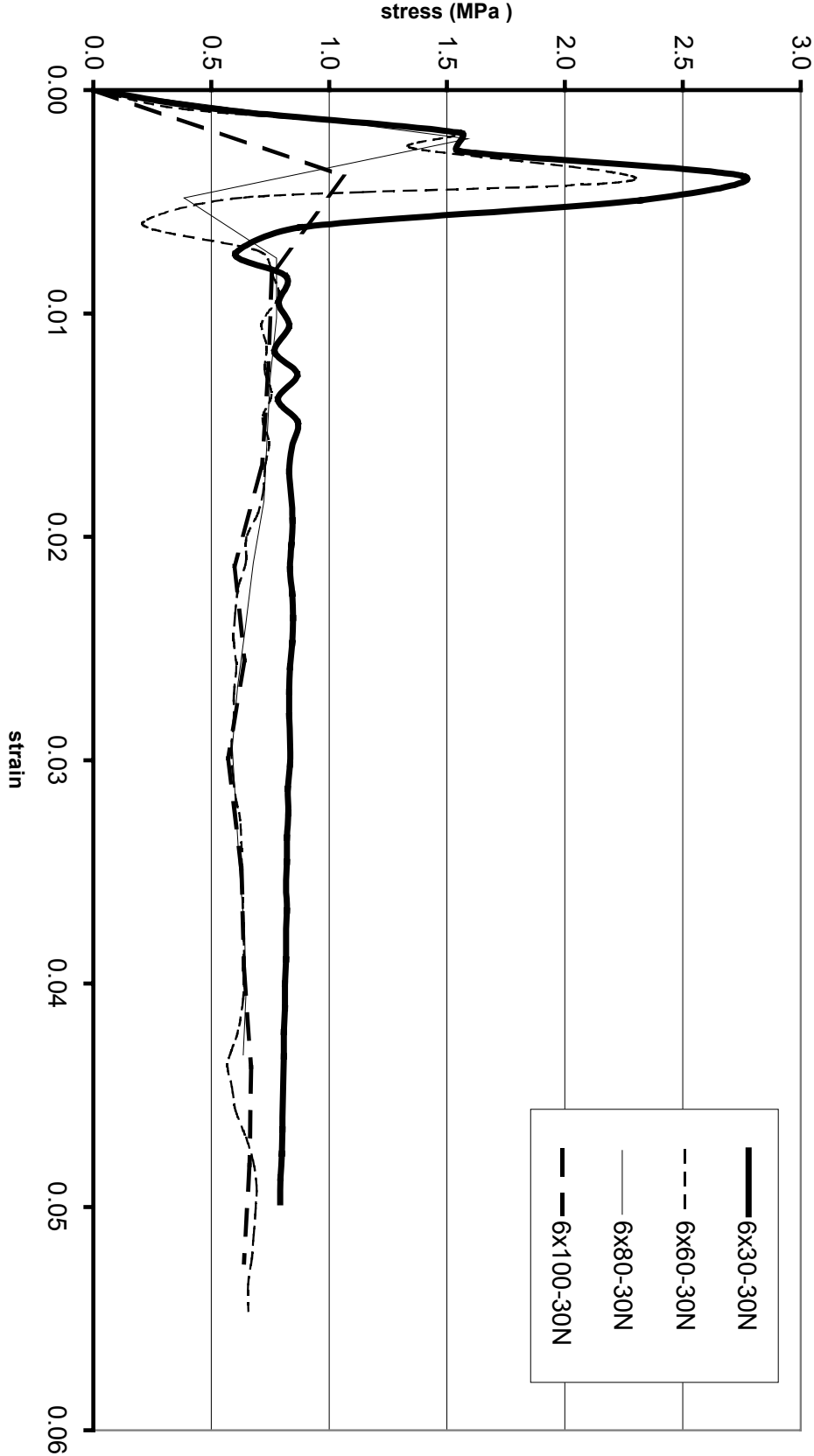
FACE of a cell

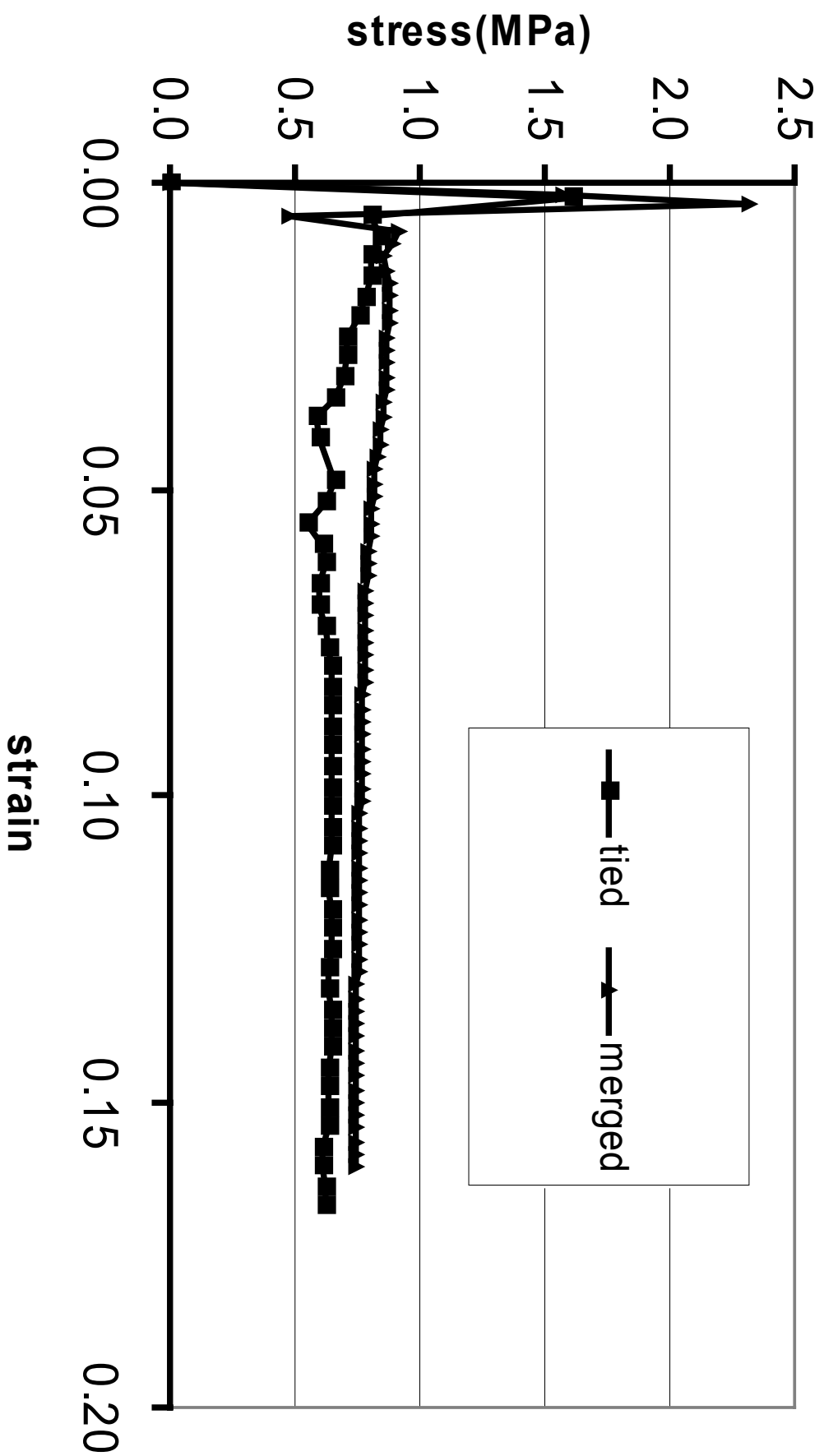


Typical force - time curve

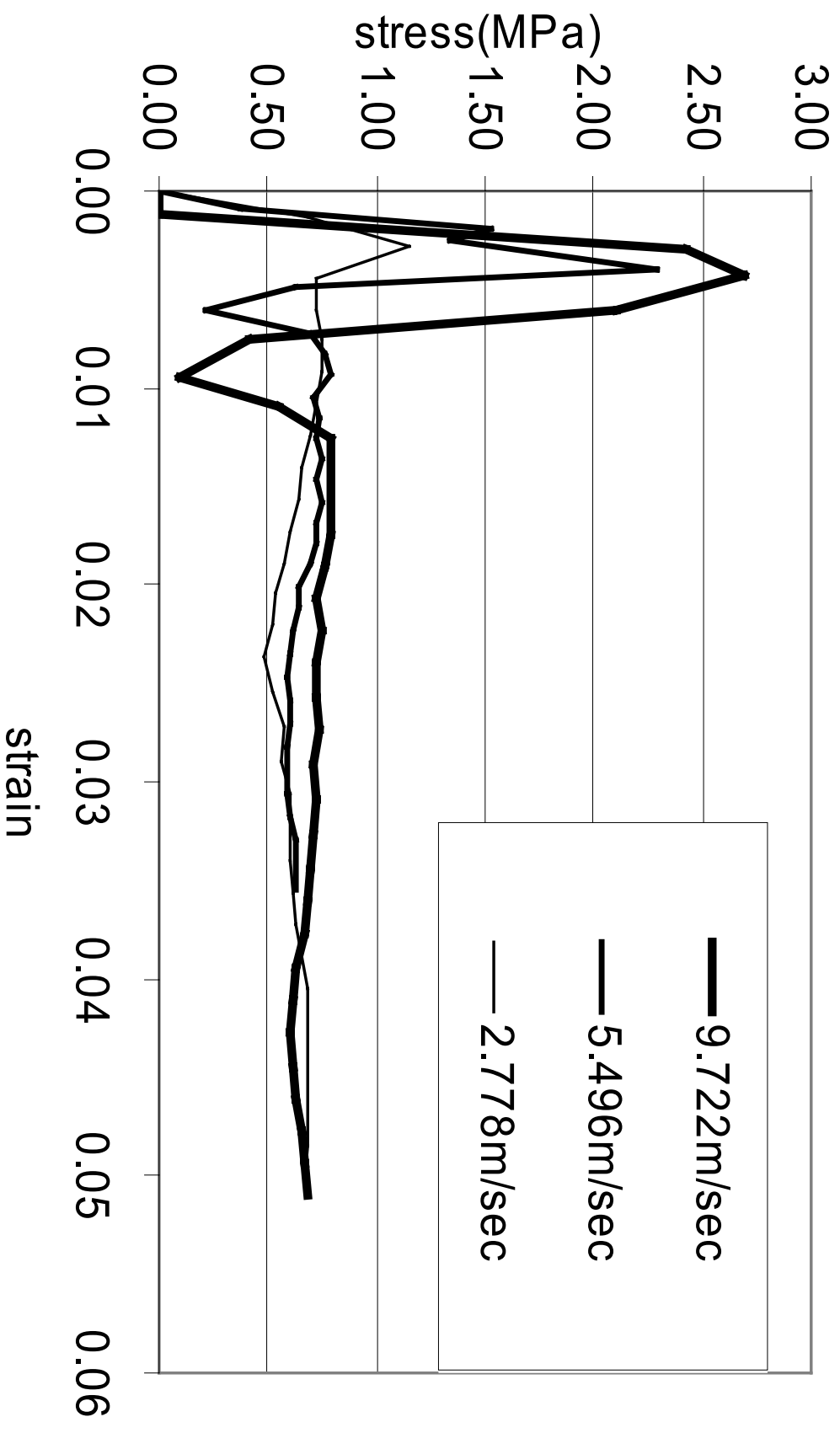


Comparison for different mesh sizes

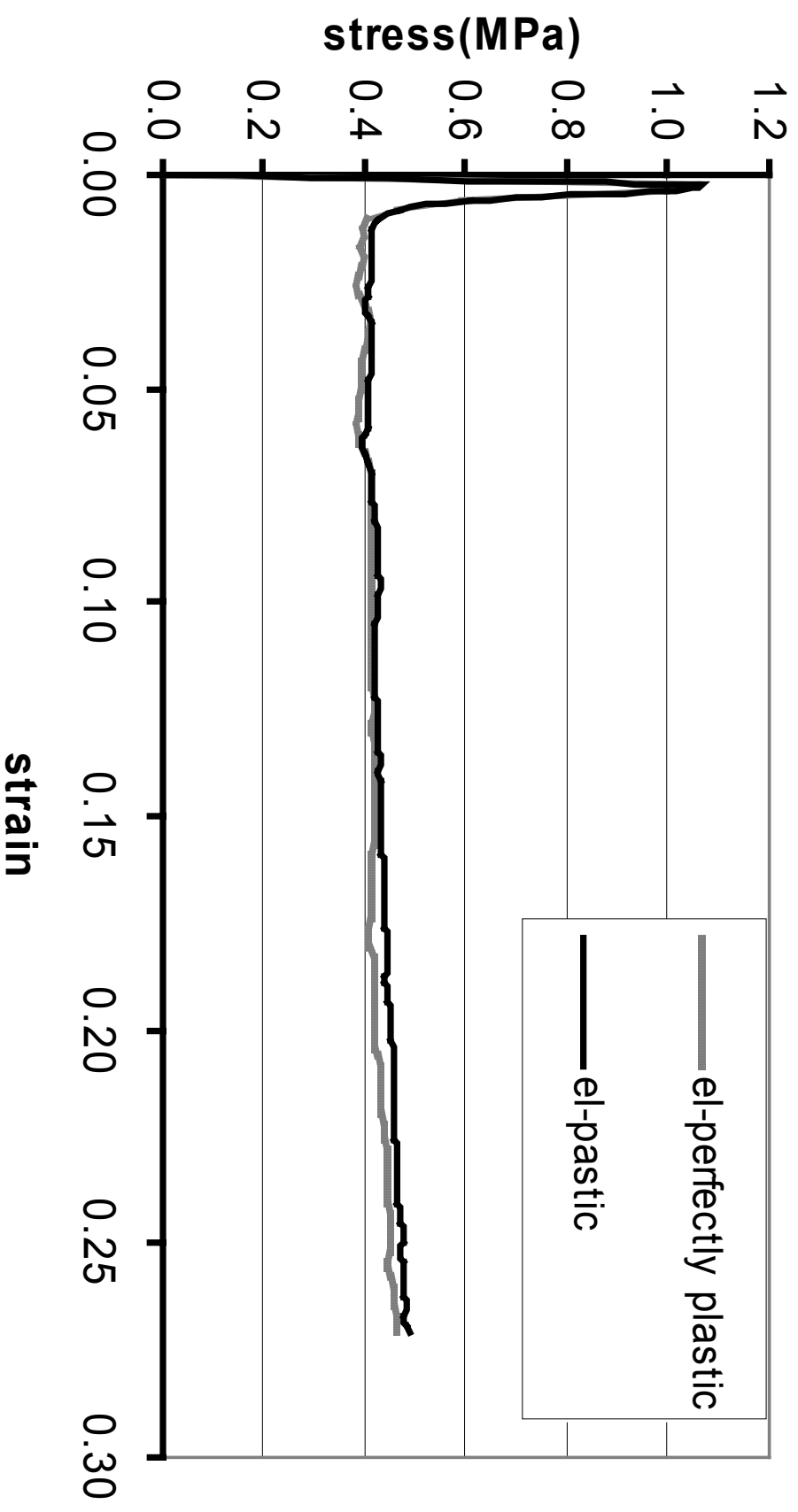


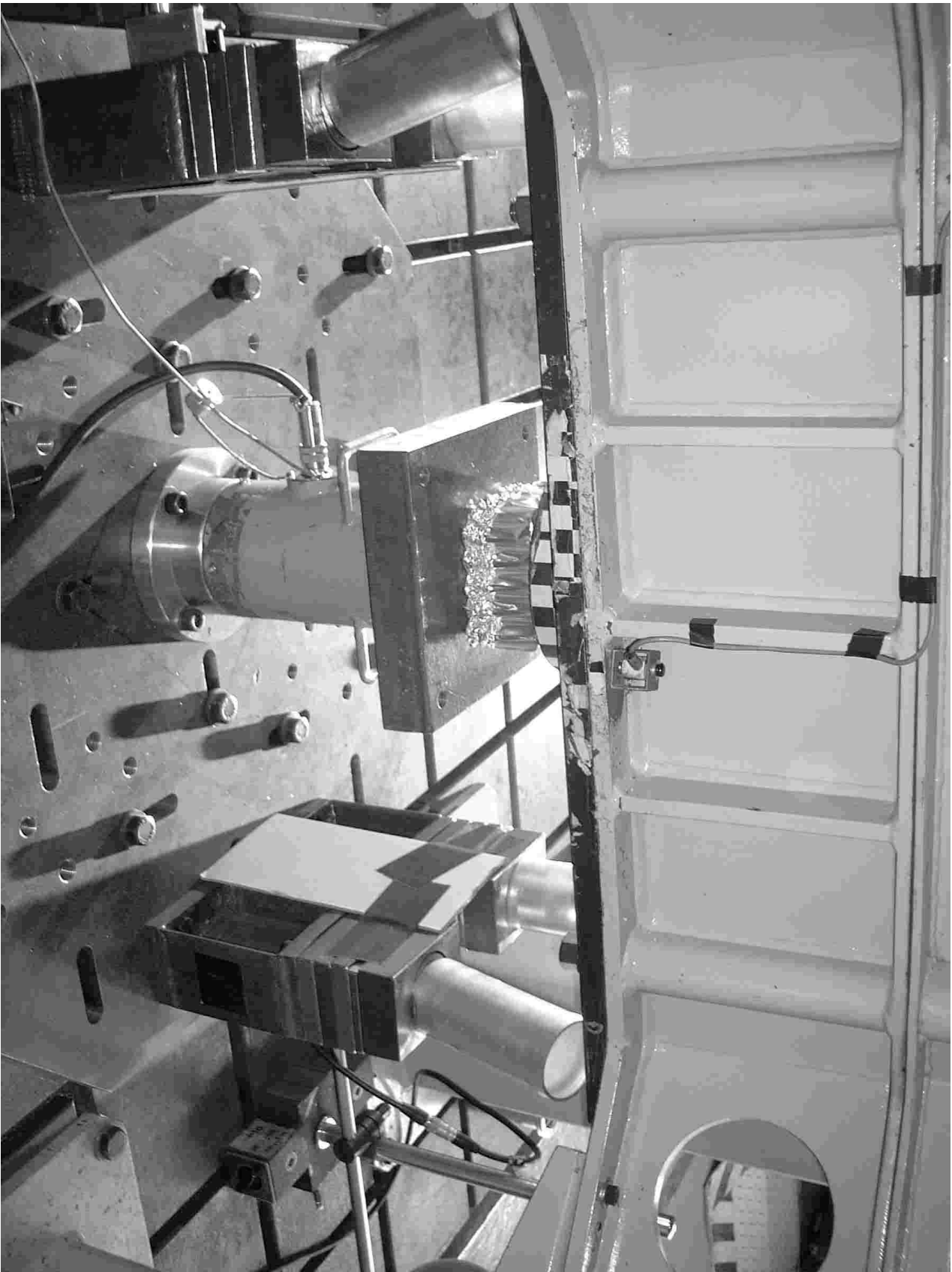


Variation with impact speed

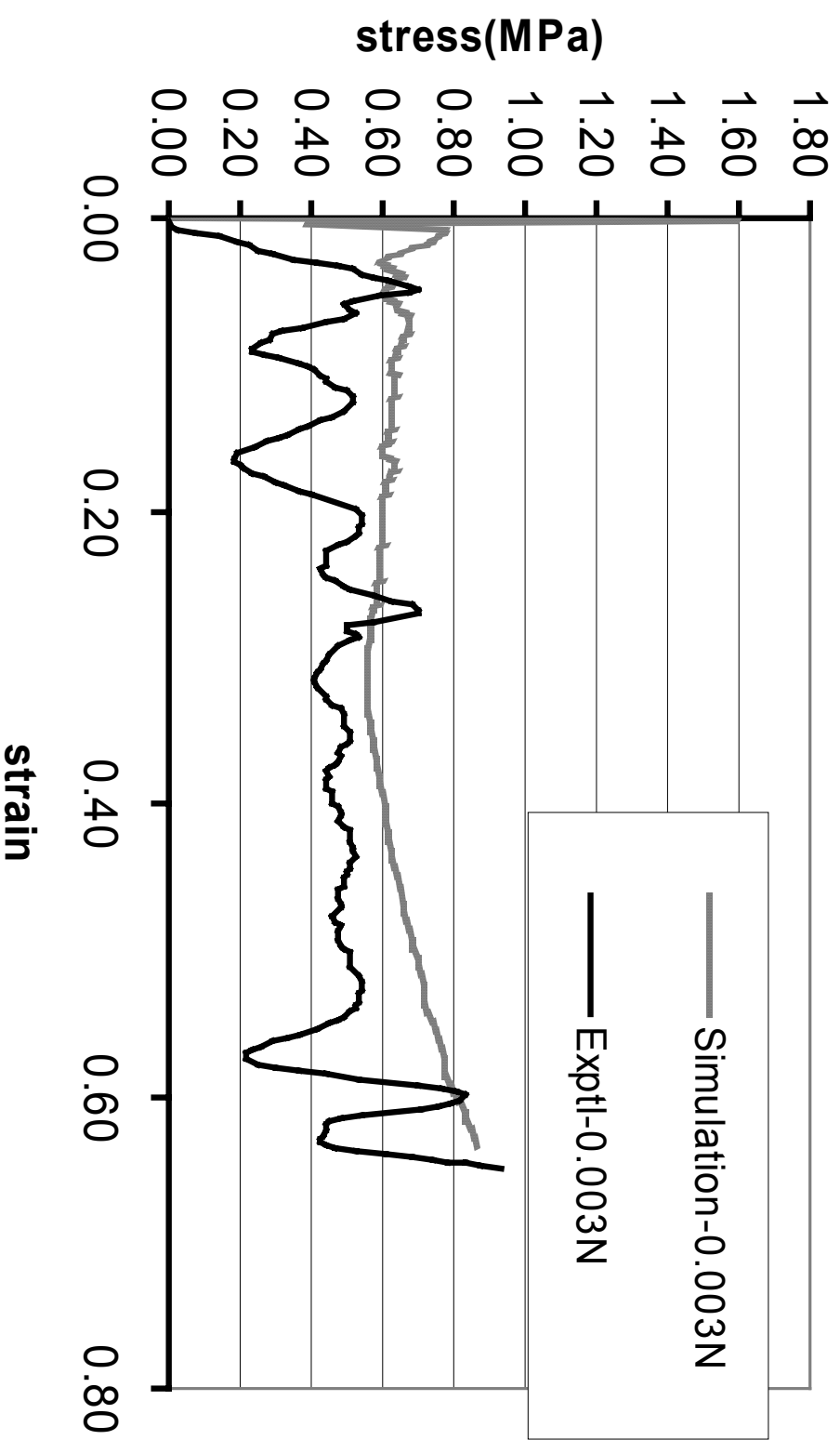


Comparison of simulation for different material models

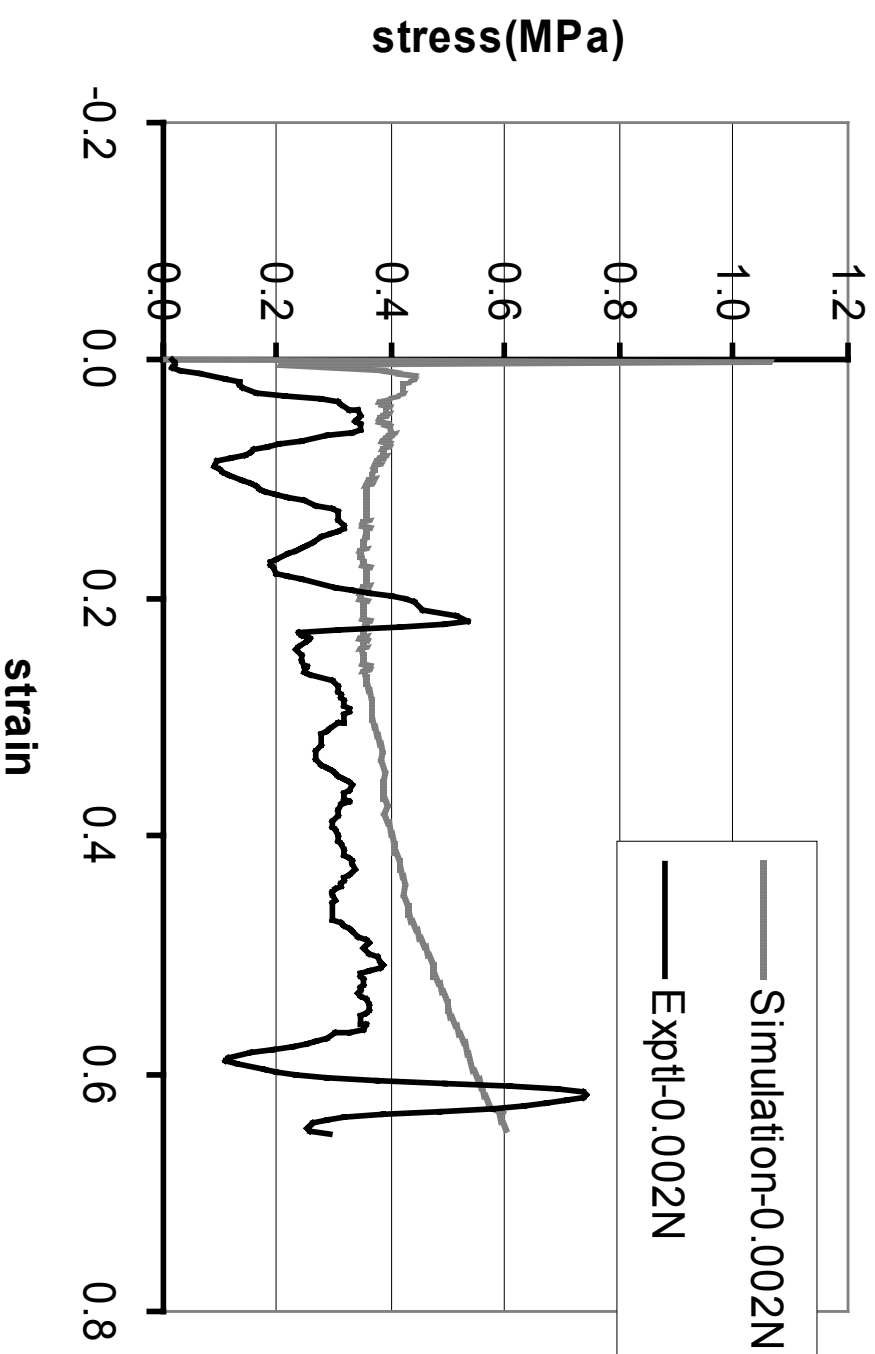




Comparison of experimental and simulation results



Comparison of experimental and simulation results - 0.002N



Dr Clive Chirwa,
Editor IJ Crash
Automotive Engineering Faculty of Technology,
Bolton Institute, Deanne Road,
Bolton, BL3 5AB, UK.

December 7, 2002

Sub: Paper "Prediction of crushing behaviour of honeycomb structures"

Dear Dr Chirwa,

We had submitted the above paper to IJ Crash and have received reviewers comments on the same from you. We have modified the paper accordingly and the modified version is enclosed. I am sending the following as desired by you:

1. Three copies of the modified paper.
2. A copy of each figure on a separate A4 size page.
3. A letter in response to the reviewers comments.
4. A CD containing the paper in MSWORD format (it includes all the pictures in a jpeg format).

There has been a short delay in responding to the paper. This is primarily because the comments were addressed to Dr Dileep Kumar but the address on the communication was mine. Please note that for all further correspondence I will be the communicating author. Kindly accept this revised submission.

With warm regards

Yours truly,

(A Chawla)