Characterization of a single 90-degrees 'UREAD' energy channel

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Abstract – Most engineering products are designed to either deliver or withstand a specific maximum force or level of energy. It is important however that the design of a structure or a machine incorporates an external or internal mechanism to overcome excessive loading, so as to reduce human discomfort and unsafe operations. Most high-energy absorption devices are not re-usable and have rebound forces comparable to those that being absorbed.

This paper examines the validity of a new concept which has been implemented into a Universal Re-usable Energy Absorption Device – 'UREAD'. The process uses a passageway of a constant cross section. Experiments were applied to devices of a single 90-degrees passageway that is constructed from intersecting channels. The experiments were carried out using different materials and different channel dimensions. The results showed a typical pattern of deformation that is associated with a continuous intense shearing with a regular force displacement diagram. Patterns of deformation zones were investigated by the Finite Element Analysis(FEA), and the predictions showed a yielding process that is dominated by shearing zones.

INTRODUCTION

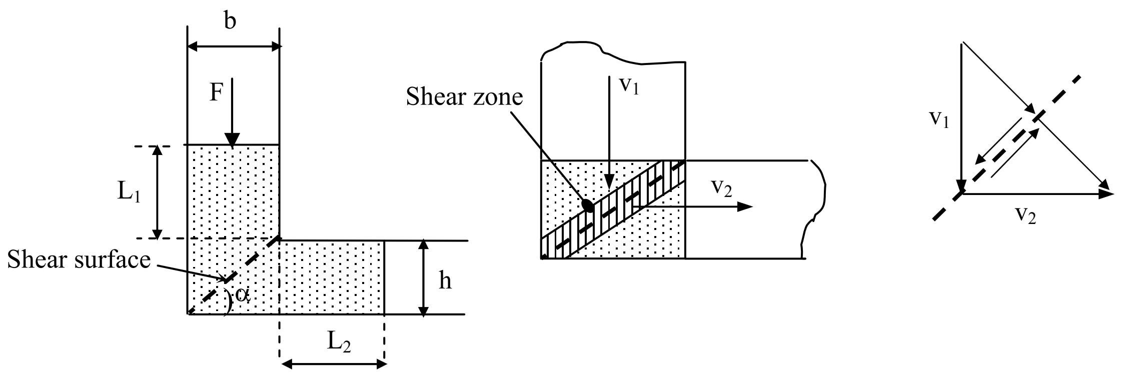
Recent advances in science and developments in engineering and technological processes brought modern life to be rather active and competitive. Innovative and fast industrial processes as well as high-speed transportations facilities are nowadays part of the high demand of new products throughout the world. As a consequence of this, risk at work or during passive life, drastically increased. Also there is, now more then ever, demand for a higher degree of personal and public protection against structural and mechanical failure. Therefore a wide market has emerged for innovative design of passive and active safety machines and devices aimed at personal, mechanical and structural protection.

In order to provide passive protection in buildings, against the energy release of severe earthquakes, for example, several techniques and devices are usually employed. When metallic dampers are used, the energy is dissipated through plastic deformation. Arrangements incorporating thin metal sheets dampers[1] may provide localized and controllable energy dissipation, at different displacement frequencies and amplitudes. However, metallic dampers designed to dissipate energy in structural applications, through the use of a deformable metallic material, may represent an alternative solutions. Robinson[2], designed a device where a billet of lead is trapped between fixing plates and forced to shear when severe external loads were effected. Friction dampers were also developed where energy is dissipated through relative motion between two elements. Dry friction provides maximum rubbing action and hence exhibits maximum resistance to motion. Devices such as the Energy Dissipating Restraint (EDR)[3] and the Friction Damper Device (FDD)[4] were designed to dissipate energy through frictional resistance between internal elements. Other properties, such as Viscoelasticity was utilised to produce dampers where energy dissipation takes place as a consequence of the shearing of particular viscoelastic materials, usually bonded between plates within the damper[5]. Devices embedded in structures were also developed such as the Tuned Mass Dampers (TMD)[6] and Tuned Liquid Dampers (TLD)[7], the absorption of energy is achieved by transferring some of the structural vibration energy to a small oscillator attached to the main structure. Each unit was tuned and designed to have the same natural frequency as the effective structure of the building. However, protection is certainly required also in other domains, such as personal safety. Nowadays, much of the development and innovations is in the personal safety of the user or operator. Body armours, made of different materials and composition [8,9], can be used as energy absorbers to protect the chest and other parts of the human body. Head protection is also a major research field, the standard design of a typical helmet[10] incorporates a rigid external shell, followed by an impact protection foam and an internal comfortable soft layer. In sport applications, legs are also subjected to severe loading conditions. Several shin and knee guards types were developed such as compressed air guards, fibreglass guards, Kevlar and plastic protections[11].

The variety of implemented devices available in the market, certainly ascertain that energy absorption is a cross discipline matter and has applications in many fields. However, researchers significantly concentrate on the design and development of energy absorption devices that could be implemented for safety in operational and personal protection. Some of the current methods may carry some disadvantages when absolute safety is concerned. These include the destruction of the protective device during the energy dissipation process, the implementation could be complex to set up, and the high demand on fashionable technologies that require innovative design, geometry and improved performance. In this paper, a novel methodology that has been exploited in the design of a Universal Reusable Energy Absorption Device (UREAD) is presented. Assessment of some of the device attributes are studied and discussed.

'UREAD' DEVICES – CONCEPT AND DESIGN

It is common in the metal forming field to relate to the idea that metals, in general, can undergo large degree of deformation, either elastic or plastic. In order to design and develop energy dissipation devices that are based on the elastic properties of metals, one must consider the rebound of the input energy after impact. On the other hand, when using on plastic deformation it is expected that permanent deformation takes place and the device needs to be replaced after impact. Osman [12] has invented a new device that has the potential of usability in almost any circumstances where mechanical shock is expected. The device is passive, i.e no rebounding and has the advantage of being reusable. The device is characterised as a Universal Reusable Energy Dissipation Device (UREAD). The energy is dissipated by plastic shearing with 100% operational reliability for repeatability. The concept of the process is based upon forcing a deformable working material through equal intersecting channels.



a) angular extrusion b) deformation pattern c) velocity components

Figure 1. Deformation pattern in 90 degrees Angular Extrusion

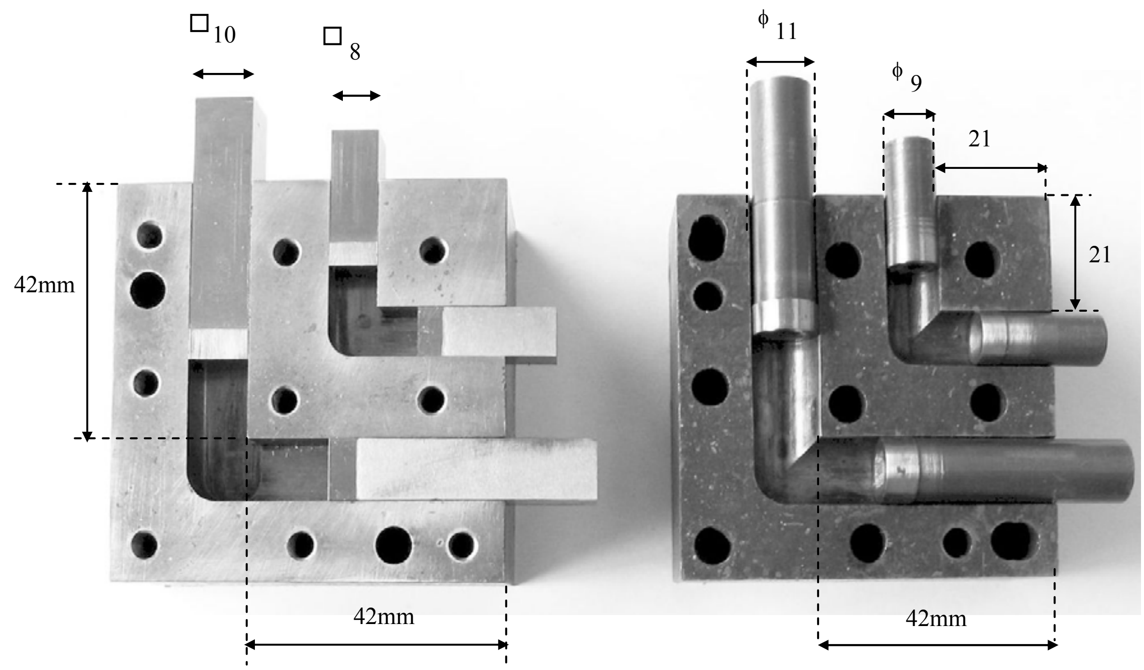
Fig. 1a shows the concept of the angular extrusion process where material is forced to deform around the corner of intersecting channels. When an external load *F* is applied to the material, energy will be absorbed by plastic deformation. Ideally, a shearing process is immediately effected in the intersection zone on a shear surface at an angle α, as shown in Fig. 1a. In practice, a shearing zone develops as shown in Fig. 1b where the material before and after the shear zone moves with the velocities v_1 and v_2 respectively. If the intersection channels are of the same cross sectional areas then the entry and exit velocities are equal, but in different direction. In such a case the process can be reversed and further impacts may be repeated several times, with the potential of being used for infinite number of cycles. The shearing process is demonstrated by the velocity discontinuity along the shear surface as shown in the velocity diagram, Fig. 1c. However, The energy level is limited by the allowable material travel, L_1 and L_2 for each channel respectively as shown in Fig 1a. In this case, the channels are intersecting at 90 degrees, the angle of intersection may vary so as to provide the required level of energy dissipation. Also, a combination of units may be used to accommodate various energy dissipation profiles[12].

In practice, a closed passageway in which deformable material is forced to pass through intersecting channels is implemented to form a Universal-Reusable Energy Absorption Device (UREAD), capable of dissipating unwanted energy in severe impact and crash. The design of such devices incorporates a base that includes the channels and two punches, one for each channel. Unit design is flexible with respect to the channels geometry and billet material. As a consequence, this new energy absorption technique reveals itself to be simple to use, with low costs and easy to manufacture. Also, energy absorption rates can be tailored to design demands.

'UREAD' 90-DEGREES DEVICES

Experimental set-up

In order to examine the applicability of the UREAD technology, channels of different cross sections, geometry and lengths were designed. A tool was designed to include as many channels as possible. Fig. 2 shows two sectioned dies each containing two channels. Fig. 2a gives the details of two square intersecting channels of 8mm and 10mm cross sections respectively, while Fig. 2b describes circular channels of 11mm and 9mm in diameters. In this investigation, all channels are of 90-degrees intersections. The units are made out of tool steel and punches were machined with a head of about 4mm to accurately fit into the channels with a shank of a smaller diameter to reduce the effect of friction between the punch and the die/channel walls. Each channel will be tested independently for a full loading cycle. The energy dissipation devices of a circular/square cross sectional area, shown in Fig. 2, were experimentally tested using commercial pure lead billets and high performance near-fluid polymeric material known as silicon gum. Lead is known to re-crystallise at room temperature and exhibits low frictional resistance. A simple compression test was conducted on the lead and the average yield strength was found to be 11 MPa.



a) Square channels b) Circular channels

Figure 2. 90-degrees UREAD testing devices

Billets were cast in special casting dies and were produced to the dimensions of the experimental square and circular channels. A hydraulic forging bench press 80kN capacity was used for all experiments. It is equipped with a strain gauged load cell and potentiometer for measuring the load and ram stroke respectively.

Operational Sequence

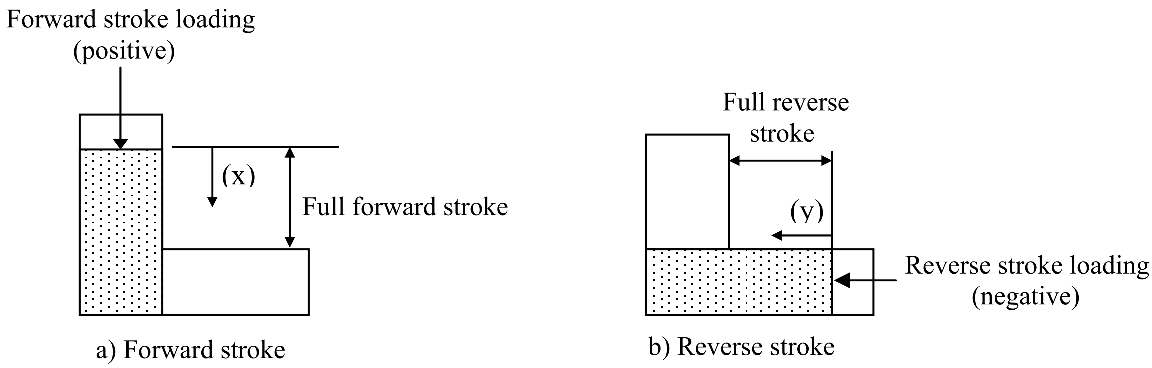


Figure 3. Forward and reverse stroke procedure

In order to characterise the behaviour of each channel with respect to the load and displacement a full cycle of forward and reverse strokes were performed on the same billet. Fig. 3a and 3b show the conventions used in the beginning of the forward and reverse strokes respectively. The tests were carried out under what could be described as static or steady state conditions. Billets of different heights were used and deformed under similar conditions. The velocity of the punch was set to around 6mm/s and both billets and channels were lubricated before each forward and reverse test. The force required to deform the material was measured against the punch displacement from the top surface of the longest billet used in the experiment, *x* for the forward stroke and *y* for the reverse stroke, as shown in Fig. 3

The experimental press operates through a vertical ram only, therefore the sequence of operations starts with the material being forced into the vertical channel until the end of the required forward stroke then both billet and horizontal channel lubricated. The unit is then rotated 90-degrees and the billet deformed to the required reverse stroke, i.e full cycle. Ideally, the material should return to its original geometry, but the material internal structure might change. However, one could engineer the material to return to its initial position and state.

'UREAD' UNIT CHARACTERISATION

In such a process characterisation may be split into two types. Geomertic characterisation which is usually given by the unit length, cross sectional area, channel profile, angle of intersection, and the dimensions of the channel secondary attributes, such as corners and edge radii. Operational characterisation includes the behaviour of the unit and workpiece material, lubrication, interface friction, loading profile and the capacity for energy absorption.

Circular Channel with Lead

The two circular channels, shown in Fig. 2b, were tested using lead as a working material. The channels are of 9mm and 11mm diameter respectively. Two tests were carried out for each channel using two billets of different height. Fig. 4 gives the loading behaviour of the 9mm diameter intersecting channels represented by the load-displacement diagram. The billets used were 25.37mm and 18.78mm in length. The punch travel was 10.41mm for the longer billet and 3.60mm for the shorter billet. The characterisation of the load-displacement diagram of Fig. 4 is implemented on the basis of the sequence shown in Fig. 3. The forward stroke is the pass of the billet from the vertical channel to the horizontal channel.

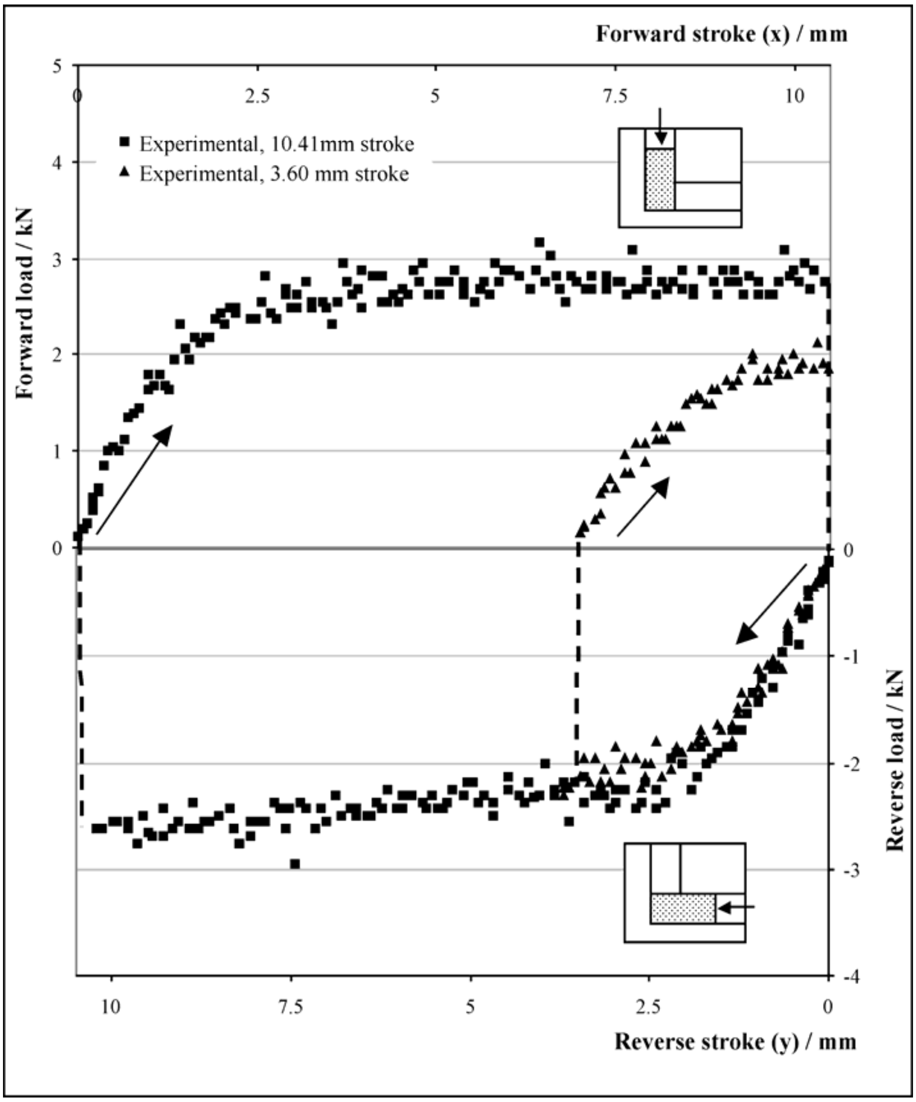


Figure 4. Experimental results for a circular unit (9mm diameter)

The loading in this case was taken as positive. When the workpiece material is pushed back in the reverse direction, from the horizontal channel to the vertical channel the loading is taken as negative. However, the displacement for the forward stroke is shown on the upper most axis, while the reverse stroke is shown on the lower most axis. The forward and reverse results are linked together to show the full operational cycle. The number of readings taken for each test was comparatively large and they were not filtered from the noise of the hydraulic circuit of the press. Therefore, slight scatter may be observed in all results but within a very controlled band. However, the trend shown by the results is quite interesting in that the load reaches a constant value as soon as the deformation pattern is initialised and effected. The average loading requirement is in the region of just under 3kN, for the longest billet giving an average extrusion pressure of just over 4 times the material yield strength. Fig. 5 gives the results of a full cycle for the 11mm diameter circular channel. In this case the billet lengths were 44mm and 27.86mm and the strokes were 25.51mm and 8.64mm respectively. The trend of the results is again similar to those obtained from the 9mm diameter channel, Fig. 4, but with higher extrusion forces. The average load for the longest billet in this case is in the region of 5kN giving an average extrusion pressure of just under 5 times the material yield stress. However, the cross sectional area in this case is about 30% higher than that of the 9mm diameter test.

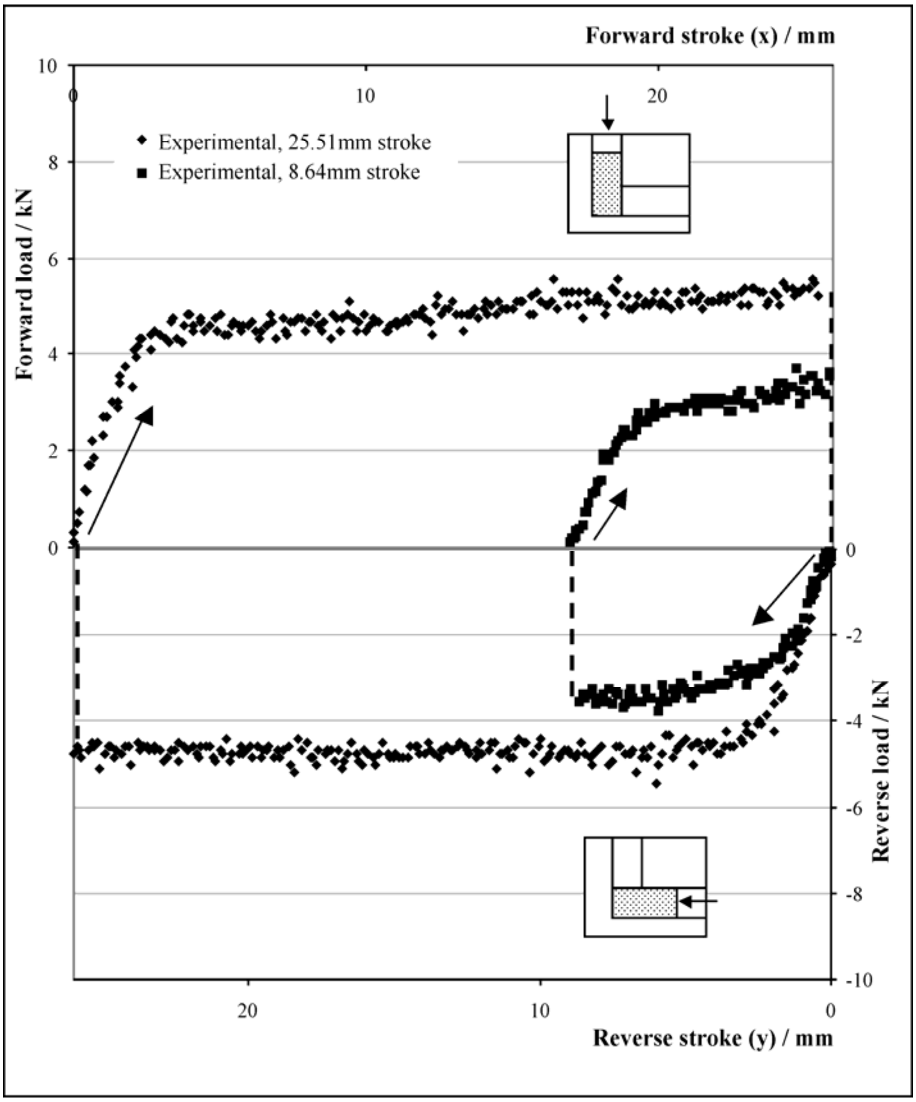


Figure 5. Experimental results for circular unit (11mm diameter)

Square Channel with Lead

The profile of the cross section of the intersecting channels in this test is a square, it differs from the circular channel in that the profile is discontinuous by the presence of the four corners of the square section. The dimensions of the cross section are 10x10mm, as shown in Fig. 2a. Two lead billets of heights 40mm and 32.6mm were used in this experiment. They were subjected to strokes of 30mm and 22.6mm respectively. Fig. 6 gives the loading results of a full cycle for the 10x10 square channel. In this case also, the load displacement diagram initially increases until a sufficient internal pressure is reached and a continuous plastic flow is initiated. The average load for the longest square billet in this test is in the region of 6kN giving an average extrusion pressure of around 5.5 times the material yield stress. For both billets the load drops slightly near the end of the stroke, this could be due to the punch reaching the top of the intersection zone where deformation is more localised.

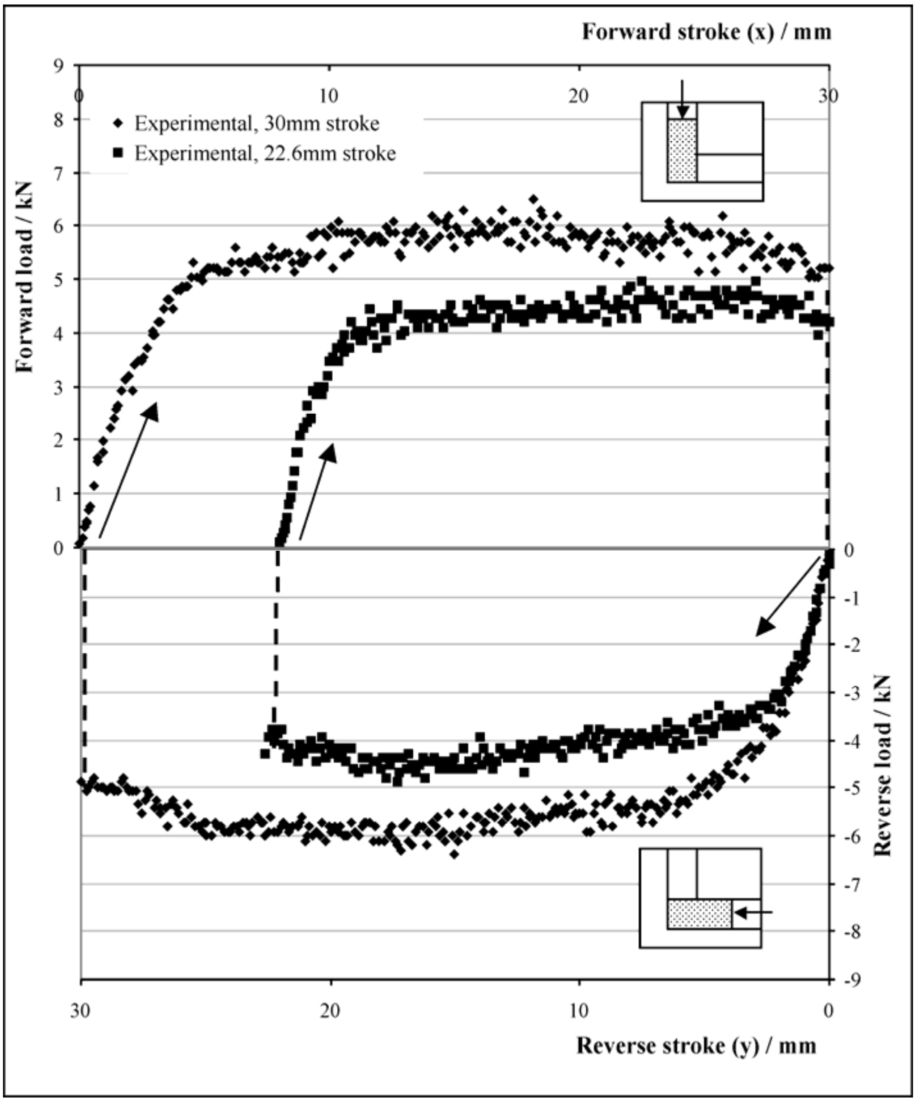


Figure 6. Experimental results for square unit (10x10mm)

Square Channel with Silicon Gum

The small square channel 8x8mm, shown in Fig. 2a, was used to extrude plastically deformable near-liquid polymeric material known as silicon gum. Fig. 7 shows the experimental average punch force against the punch displacement for a full cycle and up to a 14mm total stroke. The average pressure is in the region of 0.5MPa. The trend of the characteristic curve does not seem to vary from those obtained when using. Initially the load increases until the rate of increase diminishes where the process continues under steady state conditions. All experimental results presented here relied upon good accuracy in the process of tool making. The relationship between the straightness of the punch and the channel sides is important. If the punch would to have any interference fit with the internal sides of the channel the load would rise at such particular locations where interface friction or shearing between tool surfaces takes place. The materials used in these experiments did not exhibit strain hardening behaviour. That is why, in all cases, the load initially exhibits rapid increase to overcome friction and material yielding then the load becomes nearly constant.

The results given by these tests demonstrated that devices employing the UREAD technology to dissipate unwanted energy are capable of performing a wide range of energy absorption levels if existed within a loading mechanism. The external and internal profiles of the device could take any shape or geometry therefore it could be integrated into any structure or system easily. UREAD devices are true re-usable units. Alghamdi[13] studied the possibility of re-using thin circular conical aluminium elements in crash tests by fully inverting them from one test to another. Specimens failed after limited tests due to the cycle of high tensile and compressive straining of the elements. UREAD devices, tested several times, did not show any sign of failure due to the nature of the continuous compressive shearing process used inside the intersecting channels.

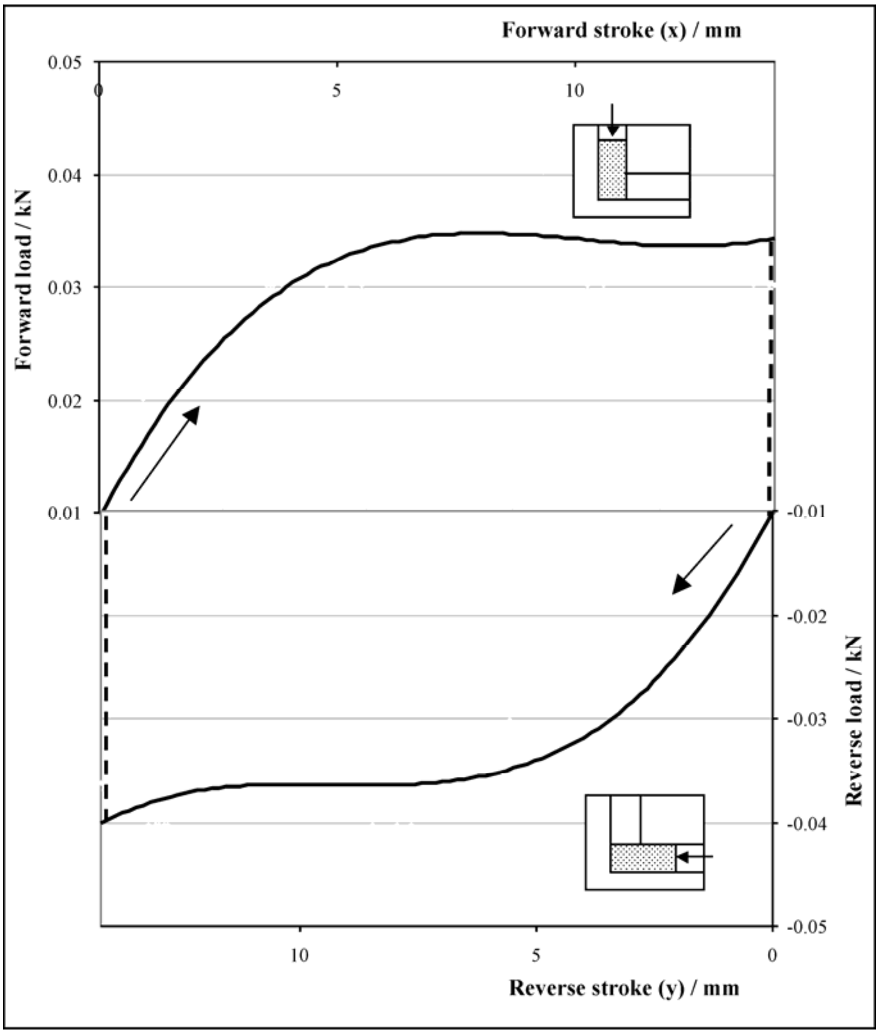


Figure 7. Experimental results for square unit (8x8mm)

MECHANISM OF DEFORMATION BY FEA

Deforming material through intersecting channels takes place by shearing at the intersection zone. Visualisation of such a pattern is not easy but by the application of numerical analysis various characteristics. A two dimensional model of intersecting channels is analysed by the Finite Element Analysis as implemented by the commercial package ANSYS. The process simulates the material just at the onset of plastic deformation process from a vertical channel, 10mm, to a horizontal channel, 5mm. Billets of different heights were used in the simulation in order study the effect of billet height on the plasticity condition. Fig. 8 shows the prediction of the distribution of plastic work in four simulations using billets of different height, shown by the billet length remaining in the vertical channel. It can be seen that the mechanism of deformation is formed through layers or bands inclined at 45 degrees and the plastic zone seems to increase in size with an increasing billet height. The trapped rigid material would undoubtedly cause an increase in the deformation load in order to overcome the elastic energy exerted on the rigid part of the billet, inside the vertical channel, and the elastic energy in the tools around it.

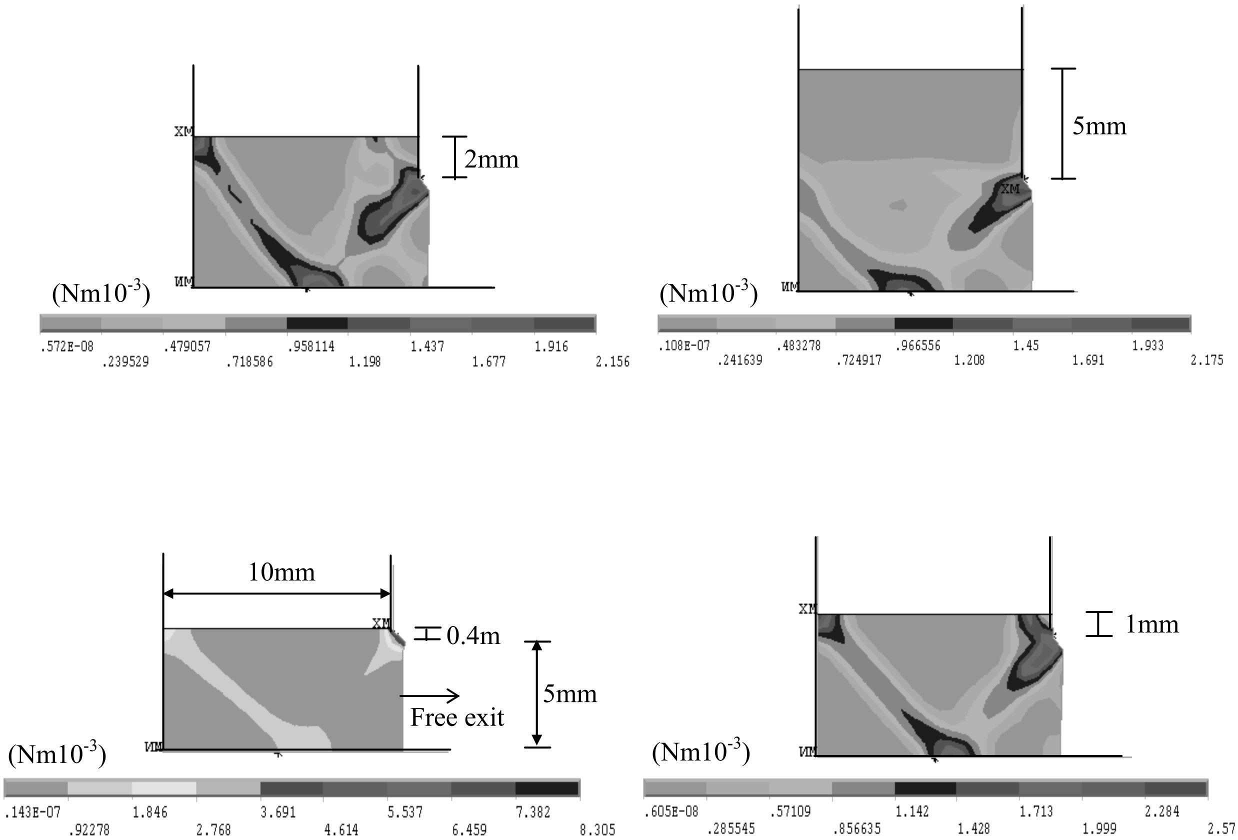


Figure 8. Predictions of plastic work by the Finite Element Analysis

CONCLUSIONS

A novel technology to dissipate unwanted energy was introduced and practical tests carried out to verify its applicable domains. Also, the concept of Universal Reusable Energy Absorption Devises (UREAD) was presented.

Devices with internal channels of circular and square cross sectional areas were manufactured and used for testing lead and silicon gum as deformable materials. All channels were designed with a 90-degrees intersection profile. The output of the experiments was in the form of the load-displacement diagram and the results were used to characterize the attributes of the channels in relation to the obtained loading profile. The billet length and its cross sectional area influence, to some extent, the loading requirements in Equal Channel Angular Extrusion. However, the capacity of the UREAD units to energy dissipation and re-usability has been demonstrated. FEA simulations were also carried out and results at the initial stages of the deformation were presented. They showed the occurrence of a deformation zone at the intersection of the channels in the form of 45 degrees shear bands.

ACKNOWLEDGEMENT

The authors wish to thank Techsil Limited, Warwickshire, UK for providing the silicon gum material used in the experiments.

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