PEDESTRIAN PROTECTION USING A SHOCK ABSORBING LIQUID (SALi) BASED BUMPER SYSTEM

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ABSTRACT

Improving pedestrian protection in vehicle impacts is achieved by the combination of proper shapes and materials in vehicle front end design. This may however conflict with other priorities regarding vehicle impact performance, such as damageability. It would be advantageous to have a single bumper system design that meets global legislative impact requirements. Alternative materials may provide the solution.

The composite material described in this paper is a blend of elastomeric capsules or beads in a matrix of Newtonian fluid. The material, which can be considered as a liquid analogy to elastomeric foams, is referred to as shock absorbing liquid or SALi.

SALi based shock absorbers have the ability to change their energy absorbing properties depending on the type of impact (velocity and size of the impacting body) that they are cushioning. Based on this ability, SALi based shock absorber devices could be beneficial for impact energy management applications because of their attendant response tailorability. However, prior to adopting SALi based devices for impact energy management applications several key issues need to be resolved.

The present study was focused on one of the most significant of these: the verification of the tunability of the response of such devices at different stroking velocities. Impact tests using an assisted drop tower facility were conducted on SALi based energy absorbers for a range of impact velocities. The results of the experimental tests conducted on SALi based shock absorbers are encouraging. The material shows innovative energy absorbing properties. Interpretation of the results described here provide for a better understanding of the fundamental behaviour of SALi based energy absorbers and provide a first step tool in optimising the design of energy absorbing bumper systems.

INTRODUCTION

Pedestrian safety is now a high profile issue within the automotive industry. All new passenger cars are required to provide an effective level of protection for pedestrians and other vulnerable road users in the event of contact. It is therefore prudent to set these standards high so that a larger number of pedestrians are protected in cases where no emergency braking takes place and to focus on the development of technologies that can meet this challenge.

Shock Absorbing Liquid (SALi) [1][2] is an innovative technology that has the potential to deliver a car bumper design that would enhance pedestrian protection without either sacrificing vehicle damageability or significantly increasing the depth of the bumper system. SALi is a mixture of elastomeric capsules – which compress to absorb impact energy – and a viscous matrix fluid – which absorbs energy as the fluid shears when the capsules compress. When packaged correctly, the result is a material that when subject to impact loading is highly efficient in absorbing impact energy and offers smart properties – soft for pedestrian impacts yet stiff for vehicle damageability. The above properties also lend SALi to other pedestrian and occupant safety applications.

However, the effective utilisation of SALi will require the correct combination of materials (with the right elastic and viscous damping properties) and mixture proportions (to minimise weight, volume and cost) to solve the impact absorbing problems of pedestrian protection. Towards this end, initial verification of the tunability of the response of such devices at different stroking velocities was undertaken. Impact tests were conducted on SALi shock absorbers at various velocities. Newtonian matrix fluids with different viscous damping properties were used with expanded polystyrene beads or polymeric

microspheres. The role of the capsules to the side of the impact zone in absorbing impact energy will be highlighted. The objective is to move towards a set of design rules for constructing SALi based impact absorbers.

The results presented provide a better understanding of the fundamental behaviour of SALi based energy absorbers and provide a useful tool for optimising the design of energy absorbing bumper systems.

BACKGROUND

Every year 1.7 million people are injured and 38 thousand people are killed on European roads [3]. Pedestrians form a large proportion of road accident casualties impacted by the front of a passenger car [4].

As pedestrians constitute a significant proportion of all road user casualties, the Commission of the European Communities (EC) has set itself the target of reducing the figure of fatalities by 30% and the injured pedestrian by 17%.

Measures were introduced by the Commission to improve the safety of vulnerable road users in case of injuries resulting from a collision with a motor vehicle [5]. The EC Directive 2003/102/EC proposed performance requirements for the frontal structures of certain categories of motor vehicles to reduce their aggressiveness [6]. It established tests and limit values based on the EEVC proposals to be complied with by new vehicles. The introduction was to be in two phases, with proposed European Enhanced Vehicle Safety Committee (EEVC) test procedure being mandatory in 2010.

Most of the current solutions designed for pedestrian protection aim at absorbing energy by deformation after impact (passive systems) [7]. A pedestrian friendly vehicle involves three requirements:

- A sufficient crush depth established by keeping adequate space between the bumper or the bonnet and the hard elements like the engine [8];
- An appropriate deformation stiffness of the crushing elements generated by energy absorbing materials to decelerate progressively the leg and the head of the pedestrian during the impact;
- An appropriate force distribution on the leg introduced by small changes in vehicle front designs.

The goal is to make the vehicle front end less injurious to pedestrian by preventing and reducing the severity of the impact.

However, there is a conflict between these goals and those for crash management as a whole. The purpose of crash management is to minimise damages at the front of the vehicle and reduce pedestrian injuries. Reducing repair costs in order to achieve a favourable insurance classification is one of the key drivers for OEMs. The level of damage is assessed in the Research Council for Automobile Repairs (RCAR) crash repair test [9]. In this test, the vehicle is crashed against a non-deformable barrier at a speed of 15km/h with 40 % overlap. It would therefore be advantageous to have a single bumper system design that meets global legislative impact requirements.

A brief discussion of the pedestrian leg impact requirements will be helpful before proceeding. The purpose of the pedestrian leg impact test procedure is to reduce the occurrence of lower limb injuries in pedestrian accidents. In the pedestrian leg impact test, a 'leg-form' impactor is propelled toward a stationary vehicle at a velocity of 40 km/h parallel to the vehicle's longitudinal axis. The test can be performed at any location across the face of the vehicle, between the 30º bumper corners. The acceptance criteria are illustrated in Figure 1. The limit values given are those used by EuroNCAP (the European New Car Assessment Programme) [10] and proposed as phase II of EC Directive 2003/102/EC [6]. The maximum tibia acceleration criterion is intended to prevent tibia fractures. The knee bend angle and shear deformation criteria are intended to prevent knee joint injuries such as ligament ruptures and intra-articular bone fractures.

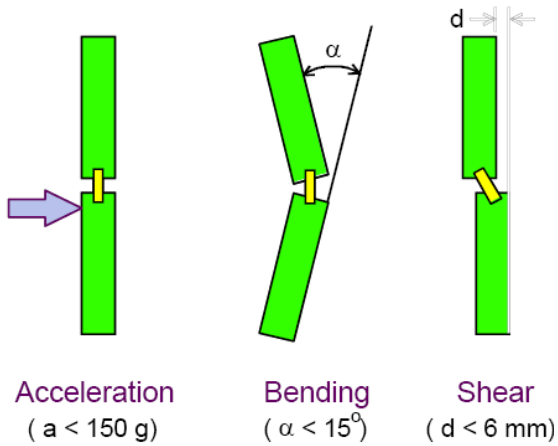

Figure 1: Pedestrian 'leg-form' injury criteria as specified by EuroNCAP and originally proposed as phase II of EC Directive 2003/102/EC.

The Commission adopted a new Proposal for a Regulation on Pedestrian Safety (and repealing the Directive) in October 2007, which forms the basis for a combination of feasible requirements with active safety measures [5]. The limit values for the

lower legform to bumper test are proposed as 170g (acceleration), 19° (bending angle) and 6mm (shearing displacement).

The front bumper is a key part in any discussion regarding lower leg impact, and - more specifically – the energy management of the bumper energy absorbing system [10][11]. In order to pass the leg impact tests, the first requirement is that the acceleration should be less than limit value. This is governed by the crush strength and depth of the bumper material [12]. Currently, plastic foams, such as expanded polystyrene (EPS) or expanded polypropylene (EPP), are the most common material used to provide energy management. The most important mechanical property these foams as an impact material are their resistance to compressive stresses. Plastic foam bumpers have been proven to perform well in single impact scenarios, but in order to prevent bottoming-out (contact and crushing occurring between opposing cell walls), there must be sufficient depth of material. The problem with increasing the depth is that it adds cost and weight to the design. In addition, like most impact materials, EPS and EPP foams absorbs the impact energy by plastic deformation, resulting in permanent damage. The softer, deeper foam recommended for leg protection will adversely affect the vehicle's ability to survive low speed collisions without damage [13].

SHOCK ABSORBING LIQUID (SALi)

Shock Absorbing Liquid (SALi) is an innovative technology that has the potential to deliver a car bumper design that would enhance pedestrian protection without either sacrificing vehicle damageability or significantly increasing the depth of the bumper system.

What is SALI?

The SALi based shock absorber is a composite material designed to absorb the energy of impacts, vibrations and shock waves. It consists of a large number of small elastomeric capsules surrounded by an incompressible matrix liquid retained in a flexible low stretch packaging (Figure 2).

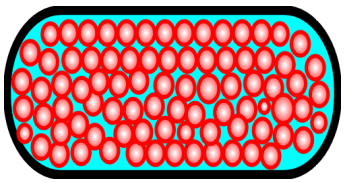

Figure 2: SALi based shock absorber showing the elastomeric capsules in red surrounded by an incompressible matrix fluid and contained within a flexible low stretch packaging.

Many different materials can be used to make SALi impact absorbers. The small capsules may be closed or open gas filled capsules, expanded polystyrene beads or polymeric microspheres for example. For the matrix fluid, any liquid which can hydraulically transfer pressure changes is potentially usable. The size and the shape of the container affect the impact energy absorbing performance. The container must be leak proof and deform easily under impact but not stretch significantly. This is to enable the capsules under and adjacent to the impact zone to rearrange themselves in the package whose front face takes the shape of the impactor.

How does SALi work?

SALi provides high impact absorbing performance, because the matrix fluid transmits pressure changes. When subject to an impact, the SALi based shock absorber combines the elastomeric properties of closed cell foams with the viscous damping and pressure equalization properties of a liquid. The matrix fluid acts as a lubricant, transmitting the stresses between adjacent capsules in the container and damping the movement of the capsules. The gas pressure inside closed capsules changes in response to pressure changes in the surrounding fluid. Before the impact, the elastomeric capsules are in close contact and incompressible matrix fluid fills all of the void space between the capsules (Figure 2). During the impact the ratio of fluid to capsule volume increases as the capsules are compressed (Figure 3).

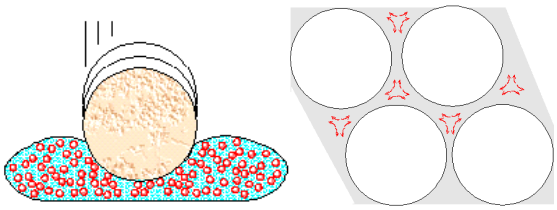

Figure 3: Hydraulic pressure causes all of the elastomeric capsules inside the bag to be compressed. The viscous liquid swirls around the shrinking capsules, contributing viscous damping to the energy absorbing effect.

What are the advantages of SALi?

The shock absorber has the ability to change its energy absorbing properties depending on the type of impact (velocity and size of the impacting body) it is cushioning. With a small impacting body, the elastic fluid is shifted sideways of the impact zone (Figure 4). The impacting body would "see" the SALi filled package as a wide, soft cushion. The matrix fluid transmits pressure changes, allowing the elastomeric material to the sides of the impact zone to also participate in absorbing impact energy.

A larger object involves a wider contact area during an impact. There would be no movement of the elastic material sideways from the impact zone (Figure 5). The rate at which the SALi material is crushed will be higher. The SALi material will have a higher stiffness. The material only exhibits these characteristics if it is packed in a stout, high tensile strength bag.

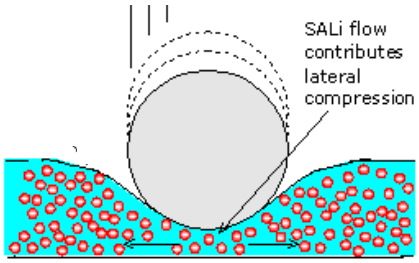

Figure 4: For a small impacting body, the elastic fluid would move sideways from the impact zone.

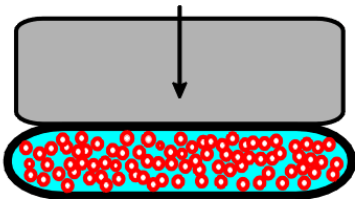

Figure 5: For a large impacting body there would be no movement of the elastic material sideways from the impact zone.

The stiffness of any foam energy absorber needs to chosen such that the stress in the plateau region is less than the specified stress. Damaging levels of impact stress travel through the foam, to the underlying surface when the foam is compressed more than about 65%. For SALi, compression, in terms of thickness change can reach 100% without leaving the plateau region, because elastomeric material flows to the side, during the impact.

At higher impact speed, energy absorption by viscous damping increases, effectively, stiffening the SALi based absorber. The use of a highly viscous matrix fluid allows the compression impulse travelling to the sides of the impact zone to be damped rapidly.

The forces applied to the impactor are fairly uniform over the contact area, which is a strong advantage against rigid foams. When correctly packaged, the hydraulic properties of SALi allow the impact loads to be transmitted over the femur and adjacent soft tissue.

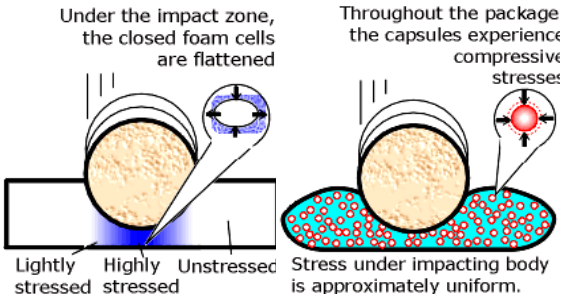

Figure 6: Stress distribution within SALi (RHS) compared with elastomeric foam (LHS).

What are the potential applications for SALi?

When looking at pedestrian protection in isolation, we can achieve the desired level of protection with traditional methods. It is a question of specifying a material with the appropriate stress / strain properties and defining the optimal geometry of the vehicle front structure. However, the manufacturer always has to balance pedestrian protection with other competing interests, such as damageability and design space constraints.

What SALi can do is offer a material that manages to balance competing interests far better than traditional solutions. The "smart properties" of SALi can resolve the "conflict of stiffness" problem. The variable uniaxial stiffness optimizes the impact absorbing abilities to provide a high degree of protection for a wide range of pedestrian sizes (from small child to larger adult body), and an adequate cushioning in impacts with other vehicles or street furniture. The SALi filled impact absorber is reusable and can accept many impacts as the capsules are uniformly compressed on all sides, take minimal damage and make a fairly recovery in volume with little residual compression when load is removed. Its energy absorbing behaviour does not change radically with the form of the impacting body, as the hydraulic pressure equalization characteristics of the absorbers allow them to absorb uniaxial impacts as a bulk compression phenomenon. It can efficiently protect occupants, pedestrians and other vulnerable road users, and minimize vehicle repair costs.

Beyond bumper systems, SALi also has potential application in:

Head Impact
- Pillar trim
- Side rail and roof lining
- Side curtain airbag attachment

Side Impact
- Upper arm & thoracic protection
- Pelvis and leg protection

Pedestrian Protection
- Under hood attachment

APPROACH

It was identified that prior to adopting SALi based devices for impact energy management applications several key issues needed to be addressed. The present study focused on one of the most significant of these, the verification of the tunability of the response of such devices at different stroking velocities (representative of the difference between pedestrian to vehicle and vehicle to vehicle impacts). This represents one of five key phases building towards the development of a SALi based bumper system:

Phase 1: Characterisation of SALi Properties
Phase 2: Further Characterisation / Simulation
Phase 3: Complex SALi Simulation
Phase 4: Real Car Simulation
Phase 5: Car Maker Tests

CHARACTERISATION OF SALi PROPERTIES

Phase one of the Cardiff University research was recently completed. The main purpose of the Phase one work was to validate our theoretical predictions of how SALi type devices work.

TEST PROGRAMME

Many formulations are possible for a SALi based impact absorber. The combination of materials and mixture proportions with the right elastic and viscous damping properties have to be found to solve the impact absorbing problems of pedestrian protection. The shock absorber should minimize acceleration and displacement during impacts with pedestrians as well as with other vehicles or street furniture. The weight, thickness and cost of the SALi filled bumper must also be at the minimum.

Phase one was concerned with mechanical testing of SALi shock absorbers. The primary objective of the experimental programme was to attest SALi Technology shock absorbing properties. Physical experiments were conducted on SALi shock absorbers to verify the innovative properties of the material and to establish its potential for pedestrian protection. Several series of tests were established with different formulations at various impact velocities.

Sample Composition and Preparation

The formulation of SALi consists of elastomeric beads and a viscous matrix fluid. Two types of beads were used for the preparation of the SALi shock absorbers: expanded polystyrene beads (diameter: 4-7mm) or polymeric microspheres (diameter: 60-90μm). The blending of the two constituent parts by volume was as shown in Table 1.

Table 1: Component part in the blending of SALi shock absorbers

Parts by volume	EPS beads	Matrix fluid
True parts	66	34
Measured parts	100	34

A third set of beads was also prepared; this consisted of the above expanded polystyrene beads blended with the polymeric microspheres. Shock absorbers using this mix of beads were referred to as nested SALi shock absorbers as the small polymeric microsphere effectively 'nest' between the larger beads. The blending of the constituent parts by volume was as shown in Table 2

Table 2: Component parts in the blending of nested SALi shock absorbers

Parts by volume	EPS beads	Polymeric microspheres	Matrix fluid
True parts	66	22.5	11.5
Measured parts	100	34	11.5

The difference between the true and actual volume (parts) is due to the volume occupied by void spaces between the spherical particles. The true volume of elastomeric material when expressed as a proportion of the measured volume is referred to as packing fraction. The volume of SALi is evaluated, and then considering that the true volume of EPS beads corresponds to 66% of the measured one, the volume is fulfilled with EPS beads and then completed with 34% extra volume of silicone oil. For instance, for a 1L sample, 340mL of oil will be added to measure 1L of EPS beads. For a nested version, 115mL of matrix fluid will be mixed with 340mL of microspheres and 1L of EPS beads. The liquid fraction is reduced from 35% to about 12%.

Every set of SALi was tested with different matrix fluids. BluStar silicone oils of 100cSt, 1000cSt and 12500cSt were used [15].

The blended mixture of elastomeric beads and matrix fluid are placed in strong polythene tubing. This tubing is heat sealed at either end (Figure 7).

Figure 7: Elastomeric material (EPS beads) blended with viscous matrix fluid. The polythene tubing retains the mixture. This is then wrapped in a low stretch outer sheath.

Test Apparatus and Procedure

Experiments were performed on an Instron Dynatup® 9250 HV Impact Test System equipped with a 15kN tup load cell and software for continuous data acquisition.

In each of the test, the SALi sample was fixed onto a steel plate as shown in Figure 8. The SALi material within the centre section was retained inside a strong, low stretch outer sheath. Without the low stretch sheath, the packaging would stretch during an impact allowing the elastomeric capsules to be displaced without suffering significant compression. The main energy absorbing mechanism would be the work done in stretching the polythene – which is fairly low, compared with the work done compressing SALi.

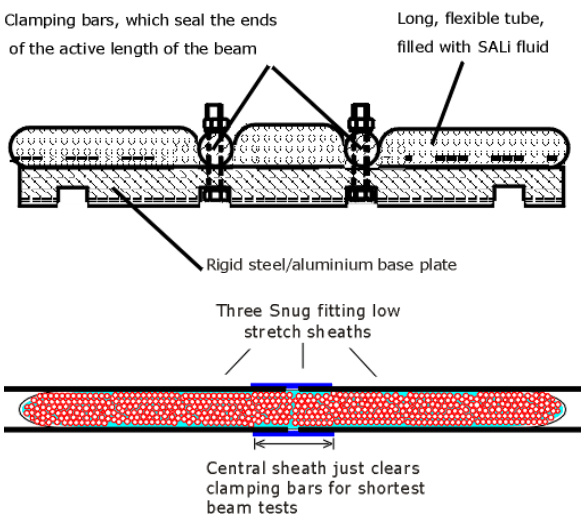

Figure 8: A holder was designed to contain the SALi absorber. The spacing of the clamping bars was adjustable to allow samples of different length to be tested.

Test Series 1

The first series of tests investigated the involvement of SALi material beyond the immediate impact zone. The impactor was a cylinder of 25mm diameter and of mass 5.2kg (Figure 9).

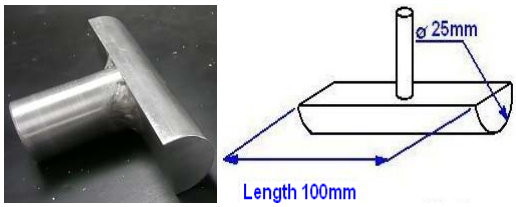

Figure 9: Cylinder shaped impactor

The longitudinal axis of the cylinder was aligned across the SALi pad. The cross section of the SALi pad was 70mm in the direction of the cylinder longitudinal axis by 50mm in the direction of the impact axis (Figure 10). The length of the pad (shown as dimension A) was varied from 70mm to 170mm in increments of 50mm. This type of impact is analogous to a pedestrian type impact described previously.

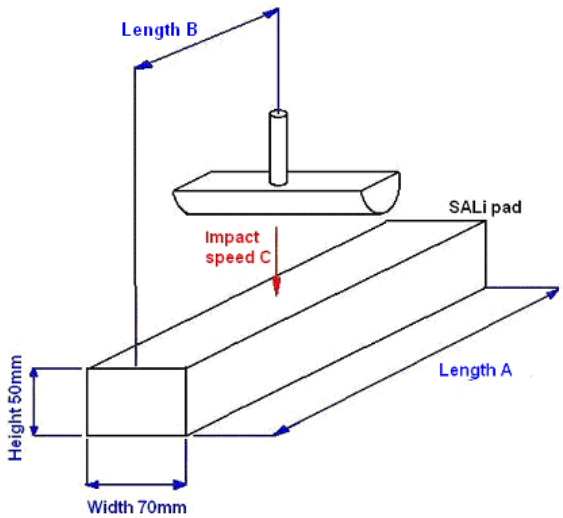

Figure 10: The alignment of the impactor and SALi sample (Length A = 2 x Length B).

The impact conditions were the same for each of the samples; the only change was the length of the pad perpendicular to the longitudinal axis of the impactor.

Fixed Parameters
- Impactor mass: 5.2 kg
- Striker shape: cylinder (25mm diameter)
- Package: polythene tubing
- Sample cross sectional area: 70x50mm
- Fluid viscosity: 1000cSt
- Capsules: EPS beads

Variable Parameters
- Impact velocity: 0.8-2.4m/s
- Sample length: 70-320mm

Test Series 2

The second series of tests investigated changes in viscosity of the matrix fluid. The experimental set-up from test series one was replicated. The change was that the sample length was a fixed parameter and the fluid viscosity was a variable parameter. The choice of sample length was based on assessment of test series 1 result.

Fixed Parameters
- Impactor mass: 5.2 kg
- Striker shape: cylinder (25mm diameter)
- Package: polythene tubing
- Sample cross sectional area: 70x50mm
- Capsules: EPS beads
- Sample length: 170mm

Variable Parameters
- Impact velocity: 0.8-2.4m/s
- Fluid viscosity: 100cSt, 1000cSt and 12500cSt

Test Series 3

The third series of test investigated a change to the capsule size. The experimental set-up from test series one was replicated. With the exception of the change in bead size, the fixed and variable parameters remained as for test series two.

Test Series 4

The fourth series of tests investigated blending EPS beads with polymeric microspheres. The experimental set-up from test series one was replicated. With the exception of the change in bead size, the fixed and variable parameters remained as for test series two.

Additional Test Series

Although not reported within the following sections, a number of additional test series were undertaken. These investigated repeatability of SALi type absorbers at various stages of the investigation, the response of EPS foam blocks and the response of SALi type absorbers to change in impactor (size and mass).

RESULTS AND DISCUSSION

Force against deflection was recorded from each of the tests. The test data was then evaluated based on what is required from a manufacturer's perspective for a pedestrian friendly bumper system. This is to limit peak acceleration (to pass the leg impact tests, the first requirement is that the acceleration should be less than limit value) and increase efficiency (the more efficient the energy management, the smaller the depth of space needed to absorb the energy from the event).

The peak load measured during the impact test was used to investigate peak acceleration (force is analogous to acceleration as impact mass was fixed).

The efficiency was investigated using the following relationship:

$$\int F(x)dx = F\Delta x\eta$$

Where:

F = Peak Force
Δx = Deflection
η = Waveform efficiency

Influence of Shock Absorber Length

The initial series of tests investigated change in absorber length upon peak load and absorber efficiency. The peak load for each of the test results is compared against change in velocity in Figure 11 and the efficiency in Figure 12.

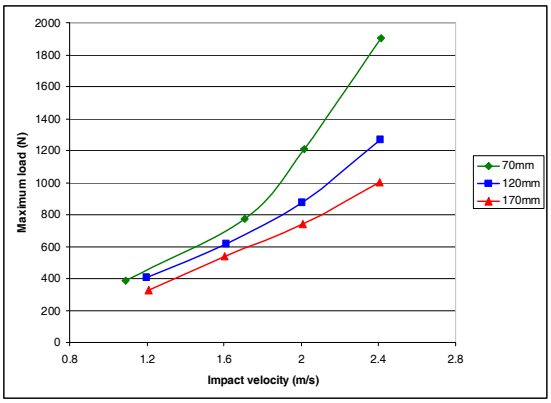

Figure 11: Maximum load variation against impact velocity with the 25mm diameter impactor and for the three SALi pad sample lengths tested.

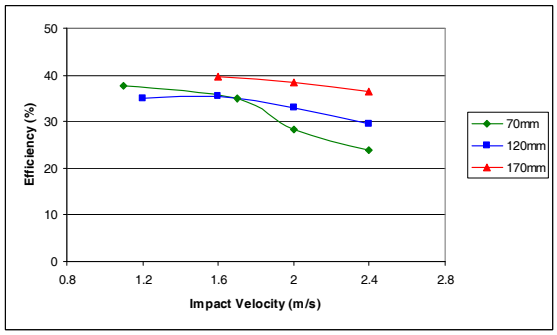

Figure 12: Efficiency with change in impact velocity with the 25mm diameter impactor and for the three SALi pad sample lengths tested.

A number of observations can be made regarding the peak load change and change in efficiency:

- Peak load decreased with pad length.
- Peak load increased with impact velocity.
- Rate of change in peak load with velocity was greater for the 70mm length sample for impact velocities >1.6m/s.
- Efficiency was highest for the 170mm length sample.

To explain these observations, it is necessary to look at the energy absorption process.

Energy absorption by a SALi composite material occurs by two mechanisms. One is the work done in compressing the elastomeric material. The other is work done by the matrix fluid as it shears. Looking at these contributions individually:

- For a given deflection, within a larger volume of SALi, the strain-rate of the individual EPS beads is reduced. Experimental work on EPS foams [17] has shown that EPS is strain rate dependent and that stress increases at higher strain rates. Therefore for a larger volume of SALi the work done in compressing the elastomeric material is reduced.

- If the strain-rate of the individual beads is less within a larger volume of SALi, then the shear rate of the matrix fluid would also change i.e. for a larger volume of SALi the state may change from i to ii in Figure 13 compared to a change from i to iii for a smaller volume. For a Newtonian fluid, the shear rate is directly proportional to shear stress. Therefore the contribution to the work done by shearing of the matrix fluid would therefore be less as SALi volume is increased.

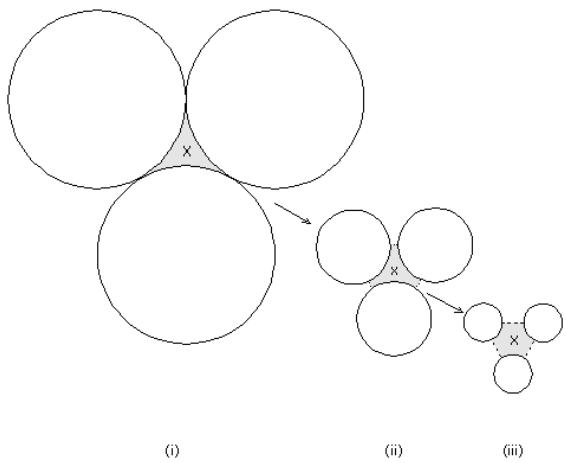

Figure 13: A two dimensional simplification of bead compression within a SALi composite fluid. The neutral point about which the fluid flows is shown as X.

The result is of the above is a reduction in work done and hence a lowering of the peak load for the same stiffness of beads and same matrix fluid viscosity. The above assumes that the pressure change is not localised, but that pressure change is distributed through the SALi fluid (this assumption will be investigated in more detail is the second series of tests).

A further observation was that the peak load increased for each of the samples at higher impact velocities. This is not unreasonable given that strain rate dependency of the EPS material mentioned earlier and that shear rate of the matrix fluid would increase (and hence shear stress).

The final observation was that whilst the change in peak load for increasing velocity was approximately linear for the 120mm and 170mm samples, this was not the case for the shorter 70mm sample.

Higher velocities considerably increase the amount of impact energy that requires dissipation. Doubling the impact speed from 1.2 to 2.4m/s increased the energy to be dissipated by a factor of 4. The higher energy impacts for the 70mm samples are compressing of the EPS beads into the densification region (region in the stress strain curve in which stress rises steeply due to contact and crushing of the cell walls). Strain hardening of EPS foam has been shown to occur at approximately 55%-65% strain region [17]. The effect of entering the densification region is a fall in the efficiency of the absorber.

Influence of Matrix Fluid Viscosity

The second series of test investigated changes in viscosity of the matrix fluid upon peak load and absorber efficiency. The length of absorber was chosen as 170mm based on observation of efficiency in the previous series of tests that showed this length of absorber to be the most efficient of the three lengths tested.

The peak load for each of the test results was compared against change in velocity in Figure 14 and the efficiency in Figure 15.

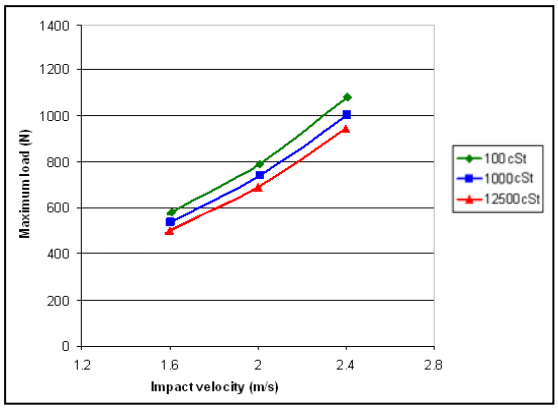

Figure 14: Maximum load variation against impact velocity with the 25mm diameter impactor and for the three matrix fluid viscosities tested.

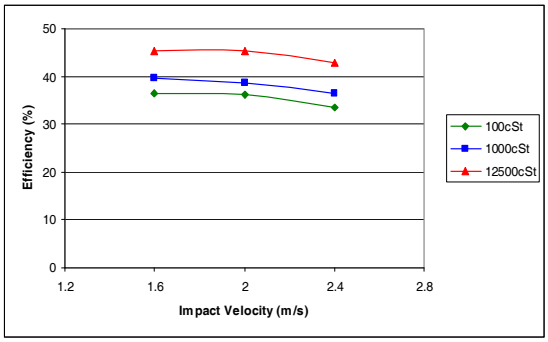

Figure 15: Efficiency against impact velocity with the 25mm diameter impactor and for the three matrix fluid viscosities tested.

A number of observations can be made regarding the peak load change and change in efficiency:

- Peak load increased with velocity.
- Peak load decreased with viscosity
- Efficiency increased with viscosity.
- Efficiency decreased with velocity.

As for the previous test series it would be reasonable to expect an increase in peak load at higher impact velocity due to the strain rate dependency of the elastomeric material (stress increases with strain-rate) and the higher shear rate of the matrix fluid (shear stress increases with shear rate).

However, as viscosity of the matrix fluid is increased, the shear stress is far greater and hence pressure change is more localised. This results is greater differential compression of the EPS beads (those nearer the impact zone suffer proportion higher strain than those further away). This can be observed by comparing the respective force deflection curves for the different viscosities at each impact velocity.

The force deflection curves exhibit hysteresis i.e. the energy dissipation during the impact results in smaller compliance during unloading (restitution) than was present during loading (compression). The area under the unloading curve equals the elastic strain energy released from the deforming region during restitution. As can be observed from the force deflection curves presented here (Figure 16), the elastic strain energy released is less for the higher viscosity matrix fluid. EPS foam is known to exhibit linear behaviour for strains less than 0.05 [17]. Therefore the greater the volume of EPS material under strain the greater the elastic strain energy released. Put succinctly, the greater the number of beads subject to compression the greater the elastic strain energy stored.

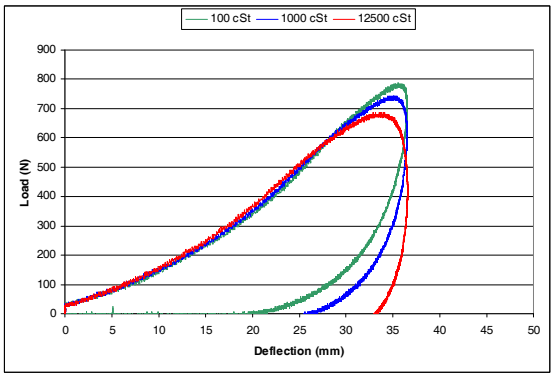

Figure 16: Force against deflection curves for 2.0m/s impact against the 100cs, 1000cs and 12500cs SALi shock absorber pads. The compliance is less for the higher viscosity matrix fluid.

Increasing the viscosity of the matrix fluid increases the efficiency of the absorber as shearing of the matrix fluid lowers the peak load

Influence of Bead Size

The third series of tests investigated changes in elastomeric beads upon peak load and absorber efficiency. The EPS beads (diameter: 4-7mm) were replaced with Expancel polymeric microspheres (diameter: 60-90 µm). The peak load for each of the test results is compared against change in velocity in Figure 17 and the efficiency in Figure 18.

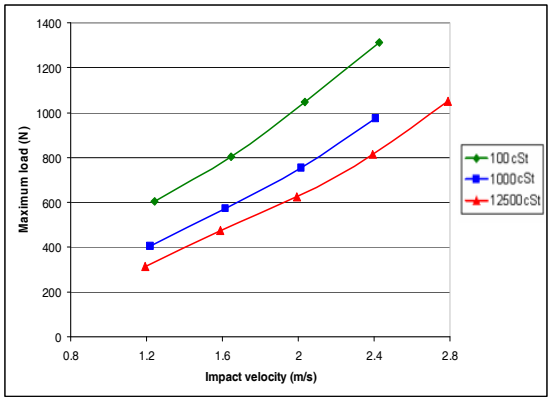

Figure 17: Maximum load variation against impact velocity with the 25mm diameter impactor and for the three matrix fluid viscosities tested.

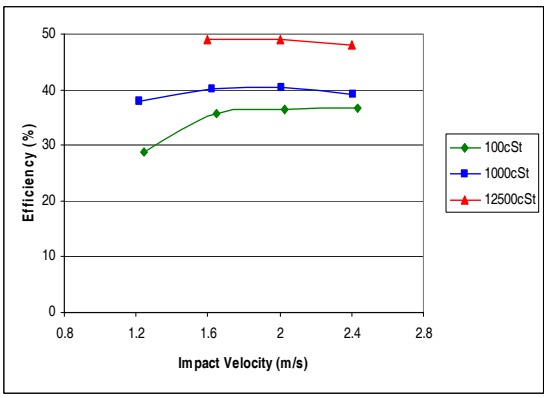

Figure 18: Efficiency against impact velocity with the 25mm diameter impactor and for the three matrix fluid viscosities tested.

Similar observations to those made for the EPS beads can be made regarding peak load and efficiency. The exceptions are that the difference in peak load at different viscosities was greater and that efficiency was maintained with increase in impact velocity. Indeed, efficiency was observed to initially increase (from 1.2m/s to 1.6m/s).

The rational for the change in load is that the contribution to the work done from shearing of the matrix fluid was greater. This follows from the fact that the total solid-liquid interface surface is higher (greater potential for shear of the matrix fluid). However, for a given level of compression the beads remain closer and therefore the mean displacement of elements of the liquid, and hence the shear rate (and hence shear stress) of the matrix fluid is reduced.

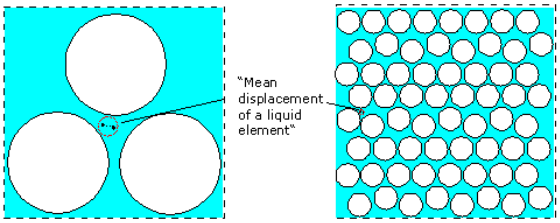

Figure 19: Comparison of SALi with different bead size. The solid-liquid interface area is higher, but for a given compression of the total volume the displacement of the fluid would be less.

The principal advantage of the polymeric microspheres over EPS beads used in the previous tests is in creating a low weight version of SALi. A mixture of liquid and polymeric microspheres used to fill the void spaces between the larger spheres would reduce the weight of the matrix fluid in the SALi shock absorber.

Combing Polymeric Microspheres and EPS Beads

The fourth series of tests investigated blending of the EPS and polymeric microspheres upon peak load and absorber efficiency. The peak load for the test with the 1000cSt matrix fluid is compared against the tests with the EPS beads and microspheres in Figure 20 and the efficiency in Figure 21.

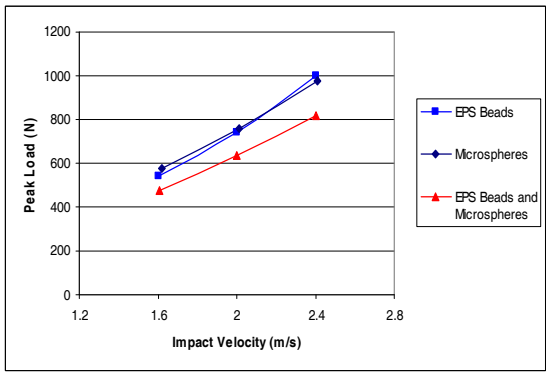

Figure 20: Maximum load variation against impact velocity for the SALi absorber using the 1000cSt matrix fluid.

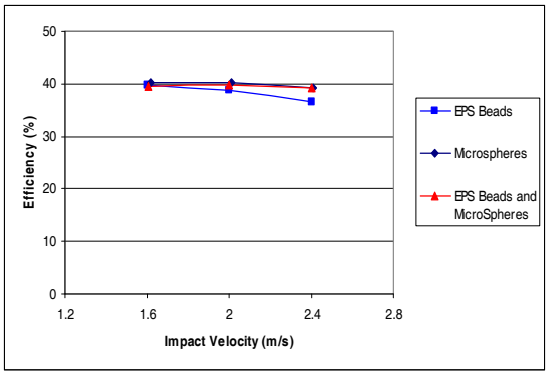

Figure 21: Efficiency against impact velocity for the SALi absorber using the 1000cSt matrix fluid.

Peak loads were lower compared to equivalent tests with just EPS or microspheres. However, the efficiency of the absorber is similar to the previous test at lower velocities and is more efficient that EPS alone at higher velocities.

This difference can be explained by assuming that the EPS beads are effectively immersed in an elastic matrix liquid. Consequently, from the perspective of the EPS beads, there is no need for the bead-to-liquid geometry to change as depicted previously (Figure 22).

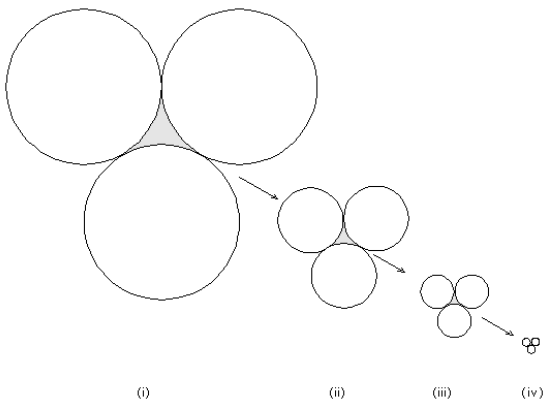

Figure 22: If the matrix fluid filling the void spaces between the EPS beads shrinks at the same rate as the beads, then there is no need for the fluid to swirl round the beads, as suggested.

For this explanation to be valid, the Microspheres and EPS beads would need to exhibit similar levels of compressive stiffness over the compression range tested.

IMPLICATIONS FOR BUMPER DESIGN

From the perspective of vehicle damageability it is necessary to have a stiff bumper to improve the vehicle's ability to survive low speed collisions without damage. The stiffness of the SALi bumper in vehicle damageability type impacts is taken to be a function of stiffness of the elastomeric material (when compared to pedestrian impacts, these are low speed events so viscous damping rate and hence viscous stress would be lower than in a pedestrian impact). Conversely, from the perspective of pedestrian protection it is necessary to have a lower stiffness. In addition, designing a bumper to fit within the packaging space typical of today's vehicle styling it is necessary to maximise the efficiency of the absorber.

The results of the experimental investigation have shown that stiffness of the SALi absorber can be lowered for small body impacts (representative of leg form impacts) without compromising the stiffness of the elastomeric material (necessary for vehicle damageability). For the same elastomeric material:

- Lengthening of the impact absorber lowered the peak load.
- Increasing the viscosity of the matrix fluid lowered the peak load.

However, the efficiency of the absorber was observed to decrease at higher impact velocities. Altering the formulation of SALi by the blending of EPS beads with polymeric microspheres was shown to maximise the efficiency of the absorber over the range of impact velocities investigated.

In addition to the above it is necessary to ensure that the strain of the elastomeric material does not reach the densification stage (strain hardening). For SALi absorbers it was shown that strain hardening could be avoided without resort to increasing the depth of the energy absorber. This provides a distinct advantage when it comes to packaging a SALi energy absorber.

Schuler et al [10] calculated the minimum energy absorber thickness for a leg impact. For foam systems it was found that a thickness of 100mm was required. A similar calculation based on the nested version of the SALi absorber (assuming similar efficiencies at higher impact speeds) would see the minimum thickness reduced to less than 60mm.

In addition, the weight of the absorber is critical. The matrix liquid is the highest density component of any SALi formulation. A mixture of liquid and polymeric microspheres can be used to fill the void spaces between the larger spheres. This would have the two advantages of (1) reducing the weight of the matrix fluid in the SALi shock absorber and (2) for a small body impact it reduces the effective stiffness. However, as long as the crush strength of the blended matrix liquid was equal to or higher than the larger spheres then the bumper stiffness for vehicle damageability would not be compromised

(the large spheres would always compress in preference to the matrix fluid).

FURTHER RESEARCH

The basic SALi formulations investigated were close packed expanded polystyrene (EP) beads, 4 to 7 mm in diameter, with the void space between them filled with a viscous liquid. This formulation is useful for helping us to understand how SALi works, but too heavy for commercial applications. A low weight version of SALi, using a mixture of liquid and polymeric microspheres to fill the void spaces between the larger spheres was also investigated.

They all shared a basic idea: to use the available package space in the most efficient manner. It means: the fast response of the energy absorbing structure to the impact event (shape force – intrusion curve close to rectangular shape), the more efficient the energy management and, therefore, the smaller the thickness of space needed to absorb the energy from the event. An important feature of the further research work will be to investigate various blends of stiff and soft microspheres, in order to increase impact energy absorbing performance.

In addition, stiff particles can be added to Newtonian liquids to convert them into shear thickening fluids. If the particle density is sufficiently high and the applied stress increases sufficiently rapidly, the fluid can lock up, to transiently mimic the properties of a solid.

SUMMARY

The purpose of crash management is to minimize damages at the front of the vehicle - reducing repair costs in order to achieve a favourable insurance classification is one of the key drivers for OEMs – and reducing pedestrian injuries – pedestrian safety is now a high profile issue within the automotive industry.

In summary, the experimental work has shown that the shock absorbing liquid composite transmits impact energy from the impact zone and through a much greater bulk of the material than would be expected of conventional solid dry foams. The result is that the stiffness of the SALi absorber can be lowered for small body impacts (representative of leg form impacts) without compromising the stiffness of the elastomeric material (necessary for vehicle damageability). The result is that forces at the impact zone that are smaller than those produced in conventional solid dry foams. Therefore, it is expected that vehicle bumpers produced from the shock absorbing liquid composite will produce comparatively less impact forces on pedestrians and will therefore be more pedestrian friendly. Key points from this work are outlined below:

- It was found that SALi provided high impact absorbing performance, because the matrix fluid transmits pressure changes, allowing the elastomeric material at the sides of the impact zone to also participate in absorbing impact energy. The investigation showed a significantly increasing performance up to 170mm (compared to 70mm and 120mm length absorbers). The forces applied to the impactor decrease with the shock absorber length, which is advantageous for pedestrian impacts. The SALi impact absorber has better energy absorbing characteristics with a higher length, which is advantageous for reducing packaging space requirement. For vehicle application, the actual values (for pad length in relation to a particular SALi composite) will depend on the size and shape of the contact area, the fluid viscosity, the impact speed and energy (these will need to be determined in the follow-up phases of the investigation).

- A highly viscous fluid was found to provide a better shock absorbing performance as loads and deflections decrease significantly with increasing viscosity. A more viscous fluid can absorb more impact energy within a smaller crush depth. The upper amount of compressible material provided by the use of very smaller polymeric microspheres instead of polystyrene beads increases the performance of SALi shock absorbers. Both loads and deflections are lower with the combination of high viscous fluid and microspheres.

- Based on observations made in this experimental investigation, a reduction in packaging space of 33% against traditional foam based systems is theoretically possible.

- The work presented here characterises SALi based absorbers in a particular impact configuration. Based on the above investigation, further possibilities have been put forward for increasing the efficiency of the absorber. Further investigation is also required in order to define design rules for SALi absorbers that seek to maximise the benefits of SALi as a crash management instrument in vehicle applications.

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