CRASHWORTHINESS OF ALUMINUM STRUCTURED VEHICLES

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ABSTRACT

Today, due to concerns about the emission of greenhouse gases and the Kyoto Protocol, there is increasing interest in the use of aluminum for reducing the weight of passenger cars to reduce fuel consumption and exhaust emissions, particularly CO_2. In recent years, several aluminum structured cars have been developed and are in service in various parts of the world, all of which have met the relevant vehicle safety requirements. However, concern continues to be raised about the crashworthiness of light weight vehicles. This paper will summarize data on the energy absorption of aluminum automotive materials and structures under impact collapse conditions as well as published information from the automotive industry on the crashworthiness of two aluminum intensive vehicles. The data and crash results demonstrate that aluminum structured vehicles can be designed to be crashworthy and to provide at least the same level of occupant protection as equivalent steel structured vehicles but at about half the vehicle structure weight.

1. Introduction

In recent years, more and more car companies have been exploring the use of aluminum for vehicle structures for reducing the weight of their cars, primarily to reduce fuel consumption and consequently CO_2 and other emissions. However, they have also seen other benefits such as improved performance without having to increase engine capacity and excellent road holding, handling and NVH (noise, vibration and harshness) characteristics, as a result of the body stiffnesses that are being achieved with both space frame and weld-bonded stamped sheet construction.

Several low volume production vehicles with aluminum structures have been introduced in recent years such as the Honda NSX[1], the Audi ASF A8[2] and the General Motors EV1[3]. In addition, Ford has built a test fleet of 40 AIV's (Aluminum Intensive Vehicles) based on the design and mechanical components of its highly successful DN5 Taurus/Sable volume production mid-sized sedan[4]. Most recently, Ford has developed its P2000 PNGV (Partnership for a New Generation of Vehicles) prototype, a purpose-designed aluminum intensive mid-sized sedan. It has the same passenger and luggage space as the DN5 Taurus and better performance but weighs just 2000lb (908kg) compared with the 3318lb (1505kg) of the current steel production DN101 Taurus[5]. All of these vehicles are significantly lighter than corresponding steel structured vehicles and especially the P2000 where Ford took full advantage of the primary weight saving from the aluminum body-in-white structure to reduce the weight of all the vehicle's secondary systems.

Driving these various vehicles reveals that they have all of the merits noted above for aluminum structured vehicles. What is not apparent and hopefully will not be experienced by driving one of these or the other aluminum structured cars that have been introduced in recent times is that they all have excellent crashworthiness. Clearly, no car manufacturer would build and sell or release for road use any vehicle that does not meet or exceed all the accepted standards for occupant safety, but there is, nevertheless, public concern that vehicles with reduced weight also have reduced crashworthiness.

There is evidence that reducing the weight of conventional cars by downsizing does reduce safety[6] but one of the major advantages of aluminum for vehicles structures is that significant weight saving can be achieved without downsizing. In particular, the length of the front and rear end crumple zones which provide the major crash energy protection system for passenger vehicles, can be maintained without adding significant extra weight.

The purpose of this paper is therefore to bring together the key test results and data for aluminum automotive materials, structural assemblies and aluminum structured vehicles pertaining to energy absorption. Taken together, this information unequivocally demonstrates that aluminum materials, when used with appropriate design approaches, are excellent materials for safely absorbing vehicle kinetic energy and therefore for building crashworthy light weight vehicle structures. In developing this paper, the author acknowledges the liberal use he has made of the benchmark data generated by present and former colleagues with Alcan. However, before presenting this information, a brief description will be given of the two major design approaches that have been used to build aluminum structured vehicles.

2. Aluminum Vehicle Design Approaches

2.1 Stamped Sheet-Based Structures

The stamped sheet or unibody design for aluminum structured vehicles is based on the approach used today with steel for essentially all high volume production vehicles and where designs have been gradually optimized to reduce mass and enhance structural stiffness, the latter being important for good handling and drivability. Honda employed this approach for the NSX, using a combination of spot and MIG spot welding to join the structure together. However, due to the lower modulus of aluminum, the body structure weight saving was limited to 40% compared with an equivalent steel design. A breakthrough came for aluminum with the development by Alcan of its Aluminum Vehicle Technology (AVT) structural bonding system using an Al-3%Mg structural sheet material (AA5754-0)[7]. The structural bonding significantly increases the body structure stiffness, particularly the torsional stiffness. In turn, this enables the weight saving compared to steel to be increased to over 50%, thereby improving the economics for using aluminum by reducing the weight used and also by giving enhanced torsional stiffness compared to spot welded steel, exceptional fatigue endurance and, as will be discussed later, enhanced impact energy absorption.

The AVT system was first used in a production vehicle for the front longitudinal crash energy management beams for the Jaguar Sport XJ220, a limited production, high performance sports car. The major applications to date are for General Motors' EV1 production electric car, for Ford's AIVs and, most recently, for Ford's P2000 PNGV prototypes. The weld-bonded aluminum body-in-white structure of the Ford AIV is shown in Figure 1.

2.2 Aluminum Space Frame Structures

The aluminum space frame approach for light weight vehicle structures was pioneered by Alcoa (8) and Norsk Hydro[9] and has been further evolved by Alumax[10] and by Lotus Cars[11]. In this approach, structural frames are built using shaped or formed aluminum extrusions which are joined by a variety of methods such as fusion welding to cast connecting nodes (Alcoa), sectioning and direct fusion welding (Norsk Hydro), compression fit forming (Alumax), and adhesive bonding supplemented by mechanical fasteners (Lotus Cars).

The first aluminum space frame production car was the Audi ASF A8. Figure 2 shows the space frame of the A8 and note the extruded tubular members at the front of the main longitudinal rails which are designed to fold like concertinas in the event of a severe collision to provide impact energy absorption. Other examples of space frame vehicles are the Renault Spider with the Norsk Hydro approach, the Lotus Elise, the Panoz Roadster (Alumax) and the Plymouth Prowler(Alcoa).

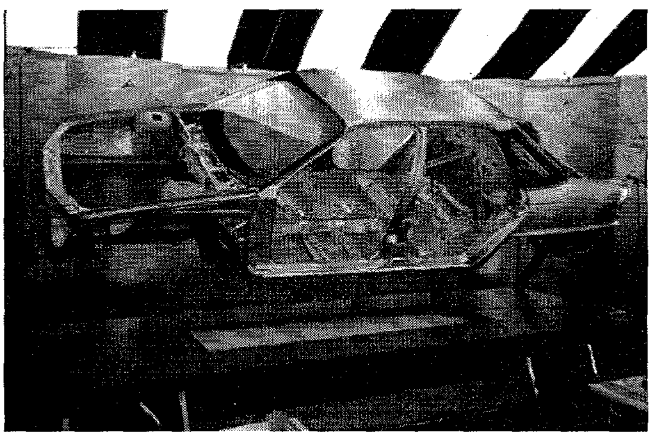


Figure 1. Ford AIV body-in-white

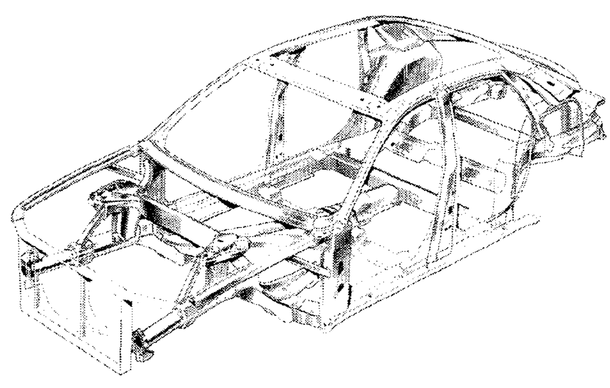


Figure 2. Aluminum space frame for the Audi A8

3. Energy Absorption and Vehicle Design

In both sheet unibody and space frame vehicles, the aluminum structure provides the main safety cage to protect the vehicle occupants and is therefore designed to remain essentially intact in a collision while the front and rear extensions of the aluminum structure (except for the Lotus Elise) are designed to collapse by concertina-type folding or controlled deep bending collapse to absorb the kinetic energy in the collision. In these two modes of deformation and hence of energy absorption, aluminum behaves exactly like steel and therefore essentially the design approach and design formulae used for steel can be used for designing crashworthy aluminum structures, provided that the appropriate mechanical properties are used.

Figure 3 shows how an aluminum structural box beam collapses by concertina folding under impact loading and Figure 4 shows the crush load for such a box beam as a function of crush distance, the "area" under the curve representing the energy absorbed. In this type of behaviour, aluminum mirrors exactly the behaviour of steel as shown in Figure 5. Concertina folding of the front and rear main structural beams is the preferred means of absorbing collision impact energy in both steel and aluminum vehicle structures since this mode of collapse provides the highest energy absorption per unit length of collapse and is also the most predictable. Thus vehicle designers go to considerable lengths to promote this mode of collapse, even for off-centre frontal impact situations.

The challenge for the vehicle designer is to design the vehicle structure and particularly the front end structure so that this collapses progressively from the front. Thus the back-up structure behind the primary energy absorbing structure must not collapse prematurely, nor must it buckle and so prevent the front members from performing their energy absorption role and yet it too may be required to collapse during the latter stages of a collision. The structure designer may also elect to have the upper front rails absorb some of the impact energy but here the designer must ensure that these do not transfer too much load to the upper green house structure and cause this to collapse. These design considerations are beyond the scope of this paper and the reader is referred to the Washington-based Aluminum Association's Automotive Aluminum Crash Energy Manual[12].

4. Mechanical Properties and Impact Collapse Behavior

4.1 Mechanical Properties - Sheet Materials

Table 1 shows the typical mechanical properties of the two most commonly used aluminum automotive sheet materials with the corresponding properties of mild steel. Of the aluminum materials, AA5754-O is the

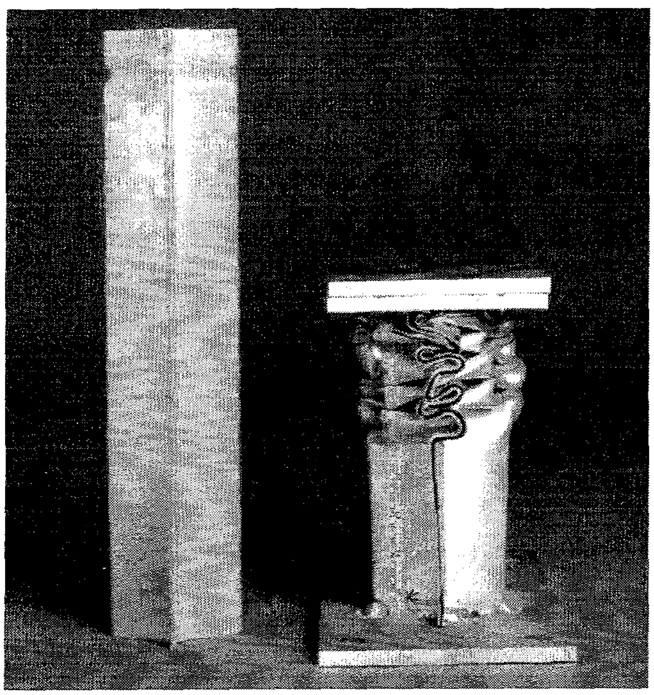


Figure 3. Aluminum hexagonal box beam before and after impact.

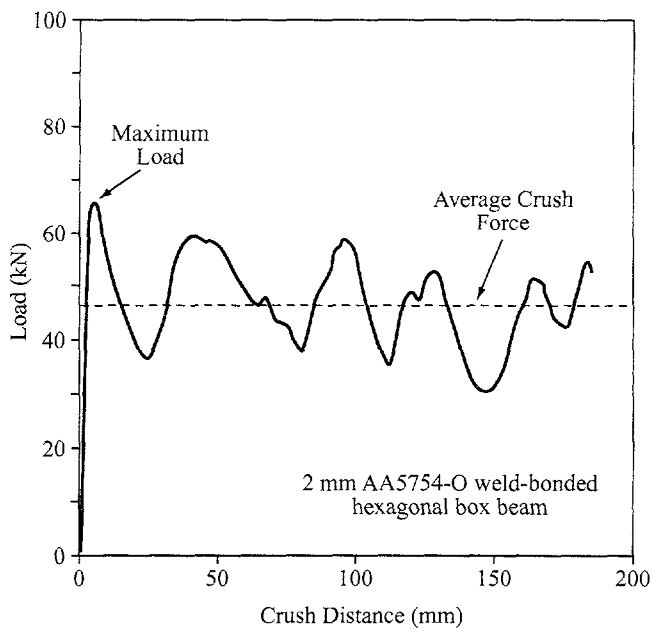
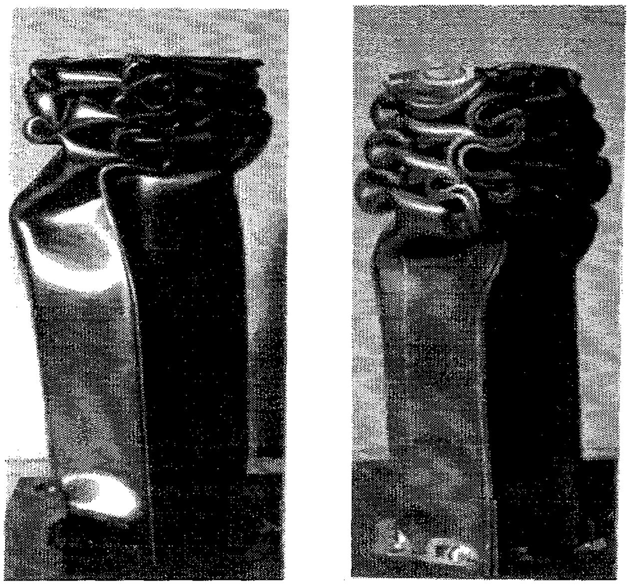


Figure 4. Force–displacement curve for slow crush testing of an aluminum hexagonal box beam.



1.2 mm spot-welded steel section   2.0 mm weld-bonded aluminum section

Figure 5. Comparative folding patterns for steel and aluminum hexagonal box beams

structural material that is used with the Alcan AVT system and has medium strength, high formability and exceptional thermal stability. AA6111-T4 has higher strength and the capability to further strengthen during a paint and or adhesive thermal cure treatment and is now the most commonly used aluminum material in North America for outer closure panels. However, it has a lower overall formability than AA5754-O and is not as thermally stable but, nevertheless, is used in certain structural applications where high strength is required and where there will be no long term exposure to elevated temperatures.

From Table 1, it is evident that the density of aluminum is just about one third that of steel, with the net result that with an aluminum sheet structure that is 50% the weight of an equivalent steel structure, the aluminum will be, on average, 50% thicker. Since the main mode of material deformation in the collapse of vehicle structures is by folding, aluminum has an advantage over steel in that, with its thicker gauge, relatively more deformation will be occurring in the aluminum as it folds and hence more of the material becomes involved in the energy absorption. This is offset to some extent by the higher strength of steel but it will be shown that with a weld-bonded structure, the same crash energy absorption as steel is achieved with a weight saving of ~ 45%.

4.2 Mechanical Properties–Aluminum Extrusions

The aluminum AA6xxx (Al-Mg-Si) alloys are the preferred ones for extrusions for automotive space frame structures due to the ease of extrusion, good formability, excellent corrosion resistance and good weldability. These alloys provide good strength at low cost, are readily formed in the T4 temper (as extruded, quenched and naturally aged) and can be used in this temper or can be artificially aged to the T5 or T6 temper to give higher strengths. Of the alloys used in space frame structures, AA6063 has the lowest strength, followed by the medium strength AA6005, 6005A and AA6061 and the high strength AA6082. The mechanical typical properties of these materials are given in Table 2.

The alloys commonly used in space frames for crash energy absorption are 6063, 6005A and 6061. The alloy 6082 is not recommended for this function because it is too strong and has a tendency to crack during folding collapse[13]. As with AA6111 sheet material, some consideration must be give to the material temper that is used, especially where crash energy absorption components will be exposed to elevated temperature during vehicle service. However, as is well documented by Court et al[13], this concern can be eliminated by overageing the materials to the T7 temper using typically 8 hrs at 210°C. This reduces the strength level from the fully age hardened condition (T6) but improves the ductility, toughness and eliminates any tendency to

Material	Elastic modulus (MPa x 10^3)	Density (kg/m^3 x 10^3)	Yield strength (MPa)	UTS (MPa)	Elongation (%)
AA5754-O	70	2.7	100	220	23
AA6111-T4*	70	2.7	180	320	25
Mild steel	205	7.85	220	370	39

**after adhesive cure treatment (~30 min at 180°C)*

Table 1. Typical material properties of aluminum and steel automotive sheet materials

crack during impact folding while providing excellent strength stability, even with long-term exposure to above ambient temperatures.

4.3 Material Strain Rate Sensitivity

It is generally accepted that aluminum alloys exhibit virtually no strain rate sensitivity but tensile tests carried out at strain rates appropriate to the collapse of impact box beams (3 to 64s-1) shows that the yield strength of AA5754 increases by about 25%. In turn, this is reflected for example in a 10% increase in the crush force at an impact velocity of 12m/s compared with that for a slow crush[14], that is, there is a dynamic factor for this situation of 1.1.

5. Box Beams in Axial Collapse

5.1 Energy Absorption

Table 3 shows the impact energy absorption for both spot welded and weld-bonded hexagonal section box beams in 2.0mm AA5754-O and for a dimensionally similar 1.2mm gauge mild steel box beam. With the aluminum beams, there is a beneficial effect from the weld-bonding which results in about a 15% increase in energy absorption and is due to the adhesive bonding causing tighter folds and hence more metal deformation. The net result is that weld-bonding with AA5754 beams gives comparable energy absorption to spot welded mild steel at about 55% of the steel weight.

The effect of testing the weld-bonded box beam at below ambient temperature is also shown in Table 3 where it is apparent that the energy absorption is enhanced at these temperatures. Experiments on the effect of the aluminum gauge indicate that the average crush force is proportional to the material gauge to the power of 1.6. In turn, this gives the energy absorbed per unit mass proportional to the gauge to the power of 0.6[14].

The effect of beam section geometry is illustrated in Table 4 and, as would be expected, essentially mirrors the shape effect found with steel box beams. This table illustrates the beneficial effects of having multiple corners in a beam section since this is where the major deformation occurs during crush. Hence the increased energy absorption of the hexagonal section compared with the top hat section. The table also shows the beneficial effect of using the higher yield strength of the T6 temper compared with the T4 temper for AA6063 extrusions. However, as noted earlier, cracking problems can be encountered with the higher strength 6xxx alloys in the T6 temper.

5.2 Predicting Axial Collapse Energy Absorption

Several method have been developed for predicting the

Alloy	Elastic modulus (MPa x 10^3)	Density (kg/m^3 x 10^3)	Yield strength (MPa)	UTS (MPa)	Elongation (%)
6063-T4			90	172	23
6063-T5	69	2.7	145	185	12
6063-T6			215	240	12
6005A-T4			115	215	22
6005A-T5	69	2.7	265	290	12
6005A-T6			265	290	12
6061-T4			145	240	22
6061-T5	69	2.7	270	300	10
6061-T6			275	310	12
6082-T4			150		21
6082-T6			310	330	8

Table 2. Typical mechanical properties of automotive extrusion alloys

Material and joint type	Average crush force (kN)	Mass relative to steel section mass (%)	Specific energy absorption (kJ/kg)
1.2 mm Mild steel Spot-welded (25 mm pitch)	52	100	14.5
2.0 mm AA5754-O Aluminum Spot-welded (25 mm pitch)	46	57	22.4
2.0 mm AA5754-O Aluminum Weld-bonded (75 mm pitch)	53*	57	25.8

**Average crush force (kN) 57.4 at -10°C, 58.7 at -40°C*

Table 3. Comparison of impact results for aluminum and steel hexagonal box beams

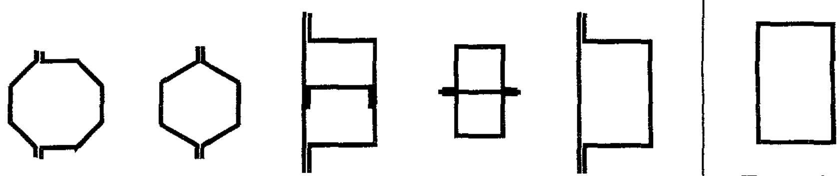
Material	2.6 mm AA5754-O sheet					AA6063	
Geometry						Extrusion	
						T4	T6
Average crush force (kN)	85	80	95	82	60	34	58
Mass-specific energy absorption (kJ/kg)	29.9	29.5	28.8	24.8	22.5	16	28

Table 4. Effect of aluminum section geometry on axial crash performance.

average crush load for box beams, the wave length of the fold pattern and the maximum force necessary to initiate the collapse process. The latter is important because it determines the strength required in the back-up structure. However, as with steel impact members, initiators are commonly used to limit this force and to control the starting pattern for the folding collapse.

It is not the intention in this paper to go into the modelling approaches that have been developed and here reference can be made to The Aluminum Association's Crash Energy Manual[12] or to McGregor et al[14]. However, it is worth mentioning a relatively simple PC based package called CRASH-CAD developed by Wierzbicki and Abramowicz[15]. Table 5 shows the excellent agreement between actual experimental results and predictions for a version of CRASH-CAD modified for aluminum for both the average crush force and the fold half-wavelength for four different AA5754 spot welded box beams. Accurate prediction of the fold half-wavelength is valuable since it shows the spot welding spacing required to facilitate the development of the folding pattern.

6. Bending Collapse

Bending collapse is the other main deformation mode that has to be considered by designers in establishing crashworthy vehicle structures. The key parameters are the maximum bending moment to initiate collapse, the energy absorbed and the mode of failure.

Failure can be by local buckling, which is typical for beams with a high width-to-material thickness ratio and is a stable and reliable mode, but the peak bending moment and the energy absorbed are low. Failure can also be by tensile tearing; this gives the highest maximum bending moment and energy absorption but there is no residual load carrying capacity after failure. This mode of failure is not common with aluminum but can occur in beams with small width to material thickness ratios. The third and most desirable failure mode is delayed buckling where buckling does not occur until the material is well into its plastic range, and such beams represent the most weight-efficient design. All three modes are shown in Figure 6.

A comparison of the energy absorption for weld-bonded beams in 1.8mm AA6111-T4, 2.0mm AA5754 and 1.2mm spot welded mild steel is shown in Figure 7 along with a schematic of the beam design. Here the tests were conducted with the crown in compression. It can be seen that the steel and the AA5754 gave similar results with the aluminum giving a 45% weight saving while the AA6111 gave the highest moment and energy absorption and represents a weight saving of 50% compared with the steel.

With bending collapse, the results obtained depend on whether the crown is in tension or in compression and also whether spot welding or weld-bonding is employed for joining. In general, it is desirable to use weld-bonding for beams fabricated from sheet and to arrange to have the crown in compression for the most likely bending collapse situation. Clearly, the above results

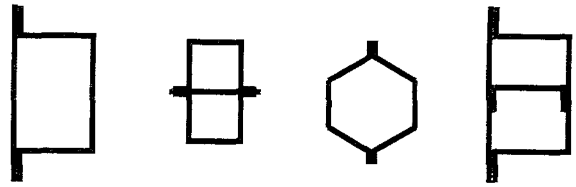
Geometry 2 mm AA5754-O spot-welded					
Average crush force (kN)	CRASH-CAD	28.1	53.2	41.9	66.6
	Experimental	26.0	49.6	39.8	70.1
Fold half-wavelength (mm)	CRASH-CAD	35.9	32.4	36.0	46.1
	Experimental	37.5	33.5	36.5	41.5

Table 5. Comparison of predicted and measured crush performance using CRASH-CAD for various aluminum section gemetries

also apply to the bending collapse of extruded aluminum beams, with these behaving much like weld-bonded beams fabricated from sheet.

Reference can be made to the paper by Meadows et al for more details on the collapse behavior of beams in bending[16]. However, the major conclusion is that, with appropriate designs, aluminum automotive structural materials can provide the same energy absorption in bending collapse as steel at weight savings of 45 to 50%.

7. Barrier Crash Data for Aluminum Structured Cars

Clearly, any car that is sold into the market must meet the relevant government safety standards but the actual crash test data is not usually available. However, Ford has released the frontal barrier crash results for a 35mph (56km/h) impact speed for one its AIV's along with the corresponding data for the regular steel production DN5 Taurus on which the design of the AIV was based[17]. This data is given in Table 6 along with the appropriate FMVSS (US Federal Motor Vehicle Safety Standard) 208 requirements for occupant crash protection. It is evident that the AIV essentially matched or improved on the performance of the regular steel production vehicle and also that both vehicles comfortably exceeded the FMVSS 208 requirements which, it should be noted, only requires at crash test speed of 30mph.

Data for a full vehicle frontal crash test conducted on the Audi A8 4.2litre at 54.8km/h (34mph) have also been released[12] and are reproduced in Table 7. Again, the

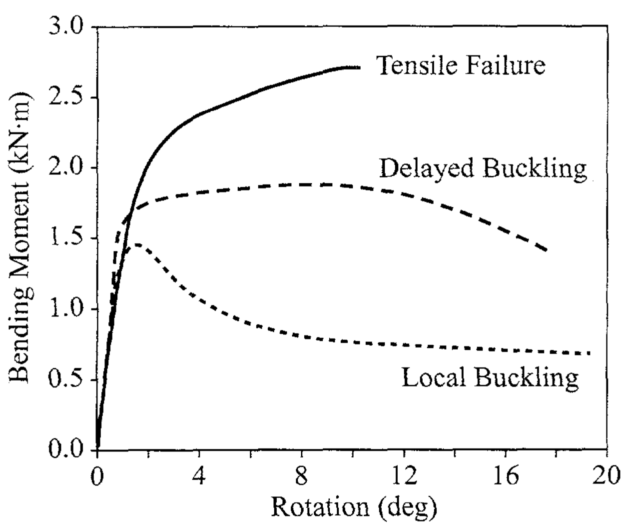


Figure 6. Moment–rotation curves, showing the three failure modes, for aluminum beams under bending

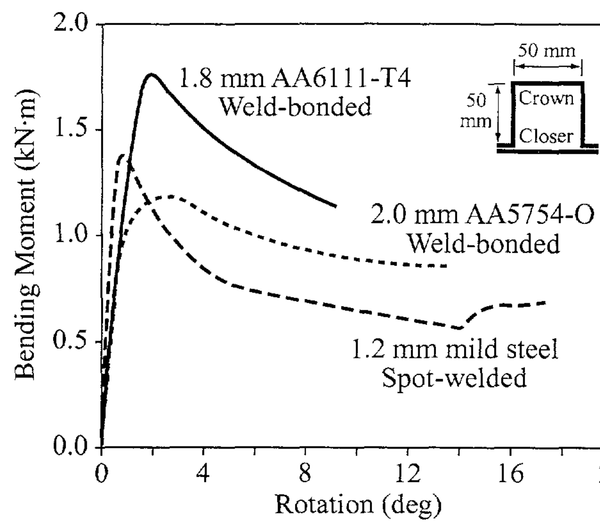


Figure 7. Comparison of aluminum and steel sections under bending with crown in compression.

	AIV	Steel (DN5)	FMVSS 208 Req.
Dynamic crash (in)	30.8	28.4	—
Head Injury Criteria (HIC)	549	524	1000
Chest accel-eration (g)	37	53	60
Chest dis-placement (in)	1.4	1.4	3.0
Torso belt load (lb)	1219	1686	—
Left femur load (lb)	697	1644	2250
Right femur load (lb)	906	1092	2250

Table 6. Frontal barrier crash results for Ford AIV and DN5 Taurus.

	Driver	Passenger	Low Risk Injury Values
Head Injury Criteria (HIC)	531	424	< 1250
Head accelera-tion (g)	61	54	≤ 90
Head pitch angle (°)	40	50	—
Chest accelera-tion (g)	56	57	≤ 60
Pelvis accelera-tion (g)	61	66	≤ 55 (56 – 75*)
Force on thighs (lb)	530	587	≤ 1349

*medium risk

Table 7. Frontal crash barrier data for 54.8 km/h impact for Audi A8

numbers are well below the FMVSS requirements and, where comparisons can be made, the results for the Audi A8 are very similar to those for the Ford AIV.

8. Conclusions

1. A number aluminum structured passenger cars have been developed and introduced into the market place with body structure weight savings of 45-50% compared with conventional steel structured cars.

2. The aluminum sheet and extrusion materials that have been developed for automotive body structure applications absorb vehicle kinetic energy from severe collision events by material folding in just the same way as the steels that are used today in vehicle construction.

3. Typically, the aluminum materials are used at gauges 50% thicker than mild steel and this increased thickness results in more material deformation in the folding process. This offsets the higher strength of steel and allows aluminum beams in both axial and bending collapse to absorb the same amount of crash energy as steel at weight savings of ~45 to 50%.

4. Design guidelines have been developed for energy absorbing members for both unibody sheet and extruded space frame structures and various modelling techniques have been developed to predict the energy that aluminum box beams will absorb. These allow effective designs to be quickly developed without the need for exploratory building and testing.

5. Published crash test results at ~55 km/h for two typical aluminum structured cars, one of unibody construction and the other a space frame design, show that these have excellent crashworthiness. In fact, both these aluminum structured cars well exceeded the US FMVSS 208 30mph (48.3km/h) occupant crash protection requirements, even at the higher test speed used.

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