

# Roof-Crush Strength Improvement Using Rigid Polyurethane Foam

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**Recent bending tests show the effectiveness of rigid, polyurethane foam in improving the strength of automotive body structures. By using foam, it is possible to reduce pillar sections, and to reduce thicknesses or eliminate reinforcements inside the pillars, and thereby offset the mass increase due to the foam filling. Further tests showed that utilizing the foam filling in a B-pillar to reduce section size can save ~20 mm that could be utilized to add energy absorbing structures in order to meet the new interior head impact requirements specified by the federal motor vehicle safety standards (FMVSS) 201 Head Impact Protection upgrade.**

**Keywords** automotive, optimize, rigid foam, safety, structure

## 1. Introduction

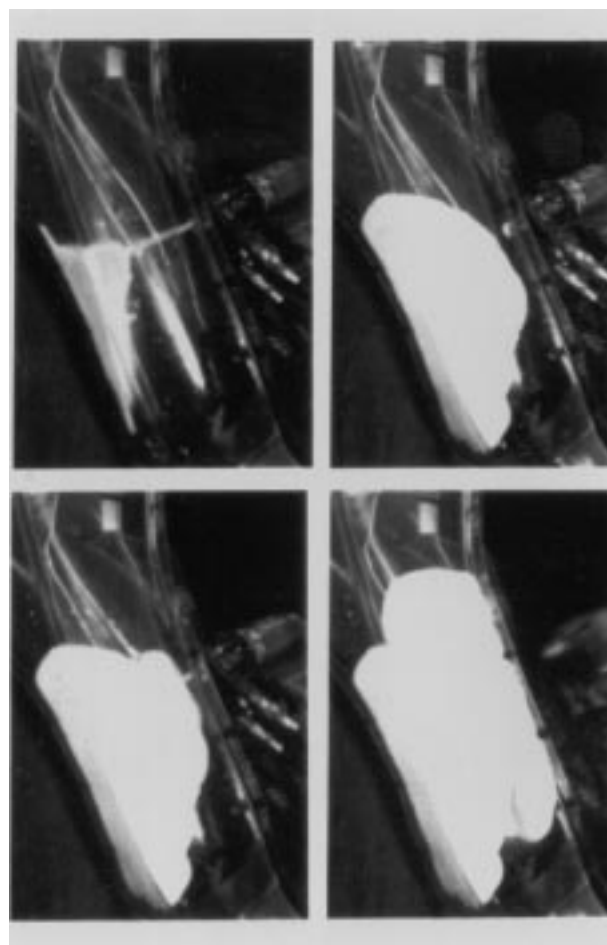
Polyurethane foam is the end product in the exothermic chemical reaction of two components, a formulated resin and an isocyanate. The two components react quickly to form a rigid, closed-cell foam. The foam expands in situ to seal cavities (Fig. 1). Low-density foam is currently being used for noise, vibration, and harshness improvement in many automobiles. The improvement is typically achieved by injecting the foam into the hollow cavities of the body sections such as the pillars, cowl, and rocker panels. With the foam-in-place process, the foam seals the cavities, thereby blocking the transmission and amplification of the wind, engine, and road noise. Other foam-sealing capabilities include sealing water and dust leaks, and reducing air leakage to optimize the heating, ventilation, and air-conditioning operation.

Higher-strength foam can provide additional benefits. In addition to blocking the noise, air, and water paths, the higher-strength rigid foam (generally referred to as structural foam) can provide stiffness to hollow body sections and joints. The increased joint stiffness improves vehicle dynamics and gives the vehicle a solid, integrated feel. The Auto/Steel Partnership, through the Ford High Strength Steel (HSS) Industry Resource Group (IRG), studied the ability of polyurethane structural foam to improve joint stiffness.

For baseline and correlation data, a production B-pillar to rocker section was tested quasi-statically. Three cases were tested: baseline (no foam), foam filled with 5 pounds per cubic foot (pcf) density, and foam filled with 30 pcf density. The 5 pcf foam improved the fore/aft stiffness by 25%, the inboard/outboard stiffness by 75%, and the torsional stiffness by 250%. The 30 pcf foam improved the fore/aft stiffness by 100%, the inboard/outboard stiffness by 200%, and the torsional stiffness by 500%. Using finite element modeling, the study optimized the section for joint stiffness, weight, and cost, by varying the metal type and gauge, and the location, quantity, and density of the foam.

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In production, a vehicle uses a 25 pcf density foam applied to the B-pillar to rocker area. Four-corner post shaker testing of the vehicle revealed that the metal in this area was fatiguing and cracking after 10% of 1 lifetime cycle. The addition of the foam allowed the vehicle to achieve 110% of 1 lifetime cycle without metal failure because of the increased joint stiffness and load distribution.



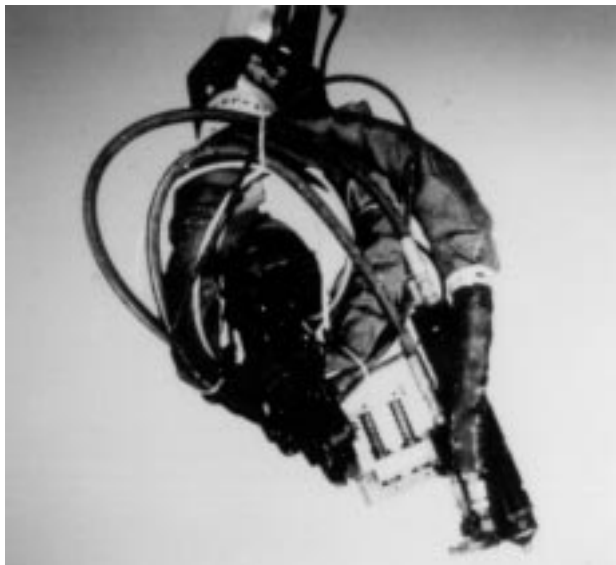
**Fig. 1** In situ application and expansion of foam

## 2. Rigid Polyurethane Foam Application Process

The application of polyurethane foam in automotive vehicles is proven technology. The foam-in-place process has been in production since 1982 and over 2 million North American cars and trucks per year use low-density and high-density foam for various purposes. Both low-density and high-density foam can be applied to the vehicle in the same application area at the assembly plant. During vehicle assembly, the foam-in-place process is performed between the paint and trim operations. The injected foam has excellent adhesion properties when applied to electrocoated or painted surfaces. Foam assumes the shape of the cavity and remains intact over the life of the vehicle. No corrosive effects or foam degradation are evident in durability testing or in production vehicles.



**Fig. 2** Current applications are performed manually using a light-weight gun with Foamseal's patented mix chamber. Robotic application is being developed and tested.



**Fig. 3** Robotic end-of-arm tooling with dispense gun

The foam process is safe and environmentally sound. It is typically applied by operators wearing safety glasses and gloves in a downdraft-ventilation booth. The foam chemicals do not contain ozone-depleting chemicals or heavy metals. The foam is also environmentally safe for landfill disposal and it has no adverse affect on vehicle steel recycling.

The foam chemicals are available in drums, returnable liquid bins, or tank trucks. Specialized equipment is necessary to heat, meter, and dispense the 1:1 volume ratio foam components. An ergonomic hand-held gun is used to mix and dispense the foam into the cavities. The injection gun is self-cleaning, requires no solvent flush, and is long-lasting. Typically, more than 250,000 shots are dispensed before gun service is required.

Presently all applications are done manually on an assembly line. Robotic application of foam is in development (Fig. 2). The end-of-arm tooling holds the material supply hoses and the injection gun (Fig. 3). This gun is the same as the ergonomic hand-held gun except the handle is removed for attachment to the robot arm.

## 3. Rigid Polyurethane Foam for Roof-Crush Strength

The industry is becoming aware of the potential of structural foam fillers as viable alternatives to conventional methods to improve the strength of the body structure. Structural composites based on epoxies, ceramics, and glass micro-bubbles are very effective, but they are not economical nor easily processed.

Rigid, polyurethane foam, however, can be cost-competitive in comparison to conventional alternatives, such as steel reinforcements. In an extensive study to reduce roof crush in controlled rollover crash tests, structural foam filling was utilized. Structural foam was added to the A-pillars and B-pillars in a recent production vehicle, to preserve the strength of the roof, add rigidity, and absorb noise and vibration, without adding significant weight. The density of the foam material is a critical parameter for strength applications, as higher density implies higher strength. However, because the mass penalty can be high as well, it is important to: a) select a suitable density range; and b) apply foam in the critical areas of deformation only. Four-point bending tests of foam-filled tubes and nonlinear finite element simulations were first performed to select a suitable density range of foam filling.

## 4. Bending Tests of Foam-Filled Tubes

Under roof-crush loading, the predominant mode of deformation is the bending of the pillars. Therefore, four-point bending tests were performed to evaluate the improvement in bending strength. An unfilled steel tube was first tested to establish its load capacity. The rectangular section steel tubes were filled with 3 pcf, 6 pcf, and 18 pcf density of polyurethane foam and the tests repeated (Fig. 4 to 6).

The deformed shapes of the end section of the unfilled tube and a filled tube (3 pcf) show that there is severe section

collapse in the unfilled tube (Fig. 7). The deformed shapes of all the filled tubes show indentations at the point of load application. These indentations are caused by the foam compression locally and they should not be mistaken for section collapse. The end sections far away from the loading points show severe collapse in the unfilled tube due to panel buckling, whereas the end sections are preserved in the filled tubes.

Although the foam is brittle and fractures beyond a certain tensile load, it is still functional, as it is entrapped within the closed section of the steel tube. This “entrapment” is a key to the maintainance or increase of the load-carrying capacity of the filled tube. The unfilled tubes show a significant reduction in the load capacity after the peak load is reached. In an open section structure, foam filling is not likely to be as effective beyond certain loading because the fractured foam would not be entrapped and would dislodge. It is also seen that the peak load of the unfilled tube is much lower than the filled tubes with various densities. The results of the tests also show that the indentations in the filled tubes do not result in a load reduction.

## 5. Numerical Simulation of the Bending Tests

Numerical simulations of the bending tests were also carried out, primarily to provide appropriate characterization of the material properties of the rigid foam material. The bending test was simulated using the transient, nonlinear code LS-DYNA3D (LS-DYNA3D Users Manual; Livermore Software Technology Corporation). Solid elements were used to model the foam, and a polyurethane foam (Material Number 57) material model was utilized. The compressive strength characteristics parallel to the direction of rise was utilized as the foam, after injection into the tube, is likely to rise along the axis of the tube, which is also the bending axis. The tensile modulus was assumed to be the same as that of the compressive modulus. An elongation limit of 5% was also assumed. The mode of deformation and load capacities computed in the simulations compared well with those obtained from the tests. A plot of the bending strength of these tubes against the density of foam shows that even a low-density foam (3 pcf) provides significant improvement, with nearly twice the bending strength of the unfilled tube. The bending stiffness of these filled tubes was plotted as a function of the density by calculating the slopes of the force-deflection curves in the bending tests at about 1 mm deflection. Again, the increase in stiffness is nearly linear with increasing density.



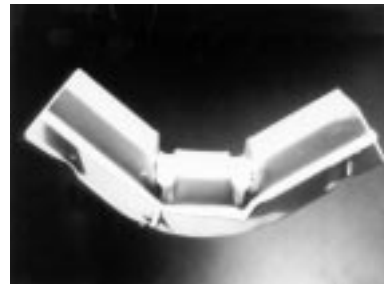
**Fig. 4** Bending test, deformed shape of tube filled with 3 pcf density of polyurethane foam

## 6. Evaluation of Roof-Crush Strength with Foam Filling

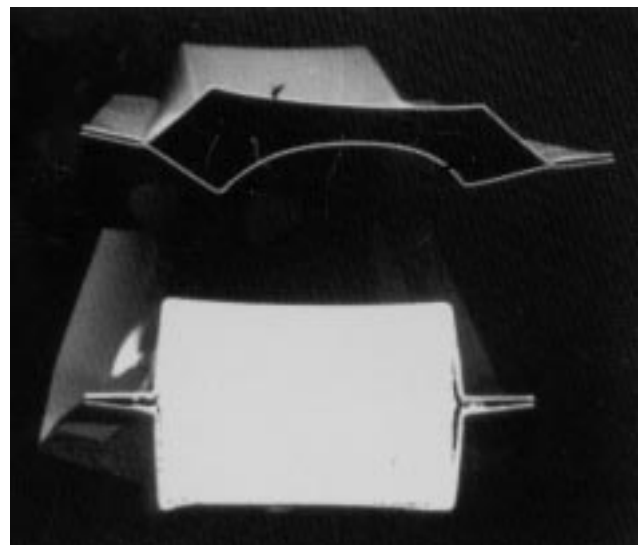
Full-scale roof-crush tests are expensive and time-consuming, so numerical simulations of the roof crush were carried out, to evaluate the effectiveness of foam, and to identify the critical areas of foam application. A finite element model of a pick-up truck cab was used to simulate the roof-crush test per federal motor vehicle safety standard (FMVSS) 216. The bending tests demonstrated that polyurethane foam can improve the



**Fig. 5** Bending test, deformed shape of tube filled with 6 pcf density of polyurethane foam



**Fig. 6** Bending test, deformed shape of tube filled with 18 pcf density of polyurethane foam



**Fig. 7** Deformation of the end sections of the tubes from bending tests.

component strength linearly as a function of the density. Several simulations were carried out to evaluate foams of various densities, and to identify critical areas of foam application for roof-crush loading.

The undeformed and deformed shapes of the unfilled structure show substantial bending about the belt-line level. Filling the B-pillar ring, the B-pillars, and the rear roof header with foam raised the strength of the roof by 72%. Having established the potential of foam filling to raise the roof-crush strength, additional studies were performed using lower densities of foam in selected regions.

The next two configurations used a much lower density of foam: the A-pillar filled with 5 pcf foam, and only the upper B-pillar filled with 5 pcf foam. Since most of the deformation of the B-pillar structure happened above the belt line, it was felt that filling the upper B-pillar would be effective in improving strength. Filling the A-pillar provided a strength improvement of only 2%. This is attributed to the fact that the B-pillar, with its considerably larger section, carries most of the load. In comparison, filling only the upper portion of the B-pillars resulted in a substantial (14%) strength improvement.

Next, a simulation was carried out with a smaller B-pillar section filled with foam, with the objective of obtaining the same strength as the original unfilled B-pillar. The aim was to offset the strength reduction of the reduced section by foam filling. This section was 20 mm narrower than the original section. First, a 5 pcf filling was used in the reduced section. The resulting strength was lower (by 5%) than that of the original unfilled B-pillar. Therefore, a higher-density foam (9 pcf) was used for the filling. This configuration resulted in nearly the same strength as the original unfilled B-pillar. Thus, it is seen that foam filling can help reduce the section sizes in the B-pillars without appreciable loss of strength or increase in mass.

## 7. Head Impact Considerations in Designing Foam-Filled Pillars

A new design concept for the B-pillar section shows that the space saved by using the foam can be used to add energy-absorbing (EA) trim or foam to help meet the proposed FMVSS 201 Head Injury Criterion (HIC) requirements for head impacts against the interior upper vehicle structure. Such space-saving is significant because thick padding of the interior upper roof structure could result in reduced interior room and reduce the driver's field of view as well. In a study that evaluated various families of foams for head impact protection, it was shown that

adding a 12.5 mm to 25.0 mm thick EA foam layer reduces the HIC values by nearly 20% in many locations.

## 8. Conclusions

Based on this study, the following conclusions can be drawn:

- Foam filling with rigid, polyurethane foam can improve the strength of the thin-walled, hollow structures such as the B-pillars. Numerical simulations of the bending tests also replicate this improvement.
- The higher the density of polyurethane foam, the higher the strength and stiffness provided to such structures. The foam density and the areas of application can be optimized for a given application based on weight, cost, strength, and stiffness improvement requirements.
- Filling the A-pillar with 5 pcf polyurethane foam did not result in an appreciable improvement of the roof-crush strength for the light truck studied.
- The upper portion of the B-pillars has been identified as a critical region for foam filling for roof crush. Also, 5 pcf density rigid polyurethane foam provides a roof-crush strength improvement of 14% with a mass penalty of 1.24 kg per vehicle.
- A polyurethane foam-filled B-pillar design concept has evolved. Although the section is 20 mm narrower, it provides the same roof-crush strength due to the added strength provided by the foam filling.
- The 20 mm space gained could be utilized to add EA structures, such as extended ribs under the trim, foam padding, or additional steel structures, to meet the recently issued head impact requirements (FMVSS 201 upgrade). This concept of foam-filled and padded hollow members could be extended to other members, such as headers and roof rails.

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