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# Quick Plastically Formed Aluminum Doors: Design and Performance

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**Door-in-white structures of left hand, front and rear steel (baseline) doors were redesigned to facilitate their manufacture from hot-blow-formed aluminum panels. The door designs each incorporated a "STAR" multi-purpose reinforcement panel. The STAR panel fulfills the functions of the traditional door intrusion beam and the outer belt line reinforcement, and also provides additional reinforcement to one of the door shut-faces. Prototype door-in-white structures were manufactured from quick plastically formed aluminum panels. Mass savings of 5.1 kg/door (front) and 4.7 kg/door (rear) were obtained in the prototype aluminum doors relative to their steel counterparts. The aluminum doors met all static stiffness criteria with the exception of upper header stiffness. FMVSS 214 testing indicated that the doors exhibited acceptable intrusion resistance when tested in the production vehicle (steel) body system. The aluminum doors also performed well in a dynamic LINCAP (full vehicle side impact) test.**

**Keywords** automotive, aluminum, fabricated metal

## 1. Introduction

Substitution of aluminum for steel can reduce mass in automotive closures (Ref 1–5). To date, aluminum sheet has been most commonly used in hoods, where the limited formability of aluminum is not a significant barrier to efficient manufacturing. Aluminum has been used much less commonly in deck lids and doors because the component panels are difficult to stamp with conventional methods unless the panels are highly simplified or divided into multiple pieces. As an example, aluminum door inner panels are commonly segmented into four or more panels that must be joined together to form an inner panel assembly.

Several OEM's have been exploring technologies that would facilitate manufacturing doors with aluminum. The Quick Plastic Forming (QPF) process (Ref 6, 7) provides one means to manufacture very complex shapes in sheet aluminum, albeit at much lower rates than are used in conventional stamping. In the QPF process, aluminum sheet is heated to an elevated temperature (400–500 °C) and formed with pressurized air against a single-sided tool.

A program was undertaken to determine the technical feasibility of hot-blow-forming the component panels for complete door-in-white structures for a door-into-roof (DIR) body architecture. The program was principally concerned with designing and building aluminum doors that would meet all product requirements. A secondary objective was to determine the feasibility of using advanced forming technology to manufacture a mass-efficient door with a one-piece inner panel. The specific baseline steel doors chosen as the target structures represented typical DIR steel doors for a premium vehicle.

The detailed door designs were done cooperatively with input from vehicle and advanced technology groups. Door structural characteristics were modeled iteratively throughout the program to ensure that the performance characteristics of the aluminum doors matched those of the baseline steel doors as closely as possible. It should be noted that a common aluminum sheet thickness was used for the inner and the multi-functional reinforcement panels due to the need to order custom material for this program. Further optimization would have been possible if different material thicknesses had been used for those two panels.

## 2. Door-in-white design

### 2.1 Door System Design

The basic door construction used a sheet-dominated aluminum door concept (Ref 8). The primary structure of the door is composed of an inner panel, an outer panel, and a multi-purpose "Simplified Total Aluminum Reinforcement" (STAR) panel (Fig. 1). The "STAR" panel concept had previously been executed for a hardtop door, and was tested successfully for static stiffness and static door intrusion. In that concept, a box-like STAR panel replaced or contributed to the function of the door impact beam, the outer beltline reinforcement, the latch reinforcement, and the hinge reinforcement. In the steel door design, additional reinforcements were added to meet specific performance metrics.

The corrugations of the STAR panel were nominally offset 5 mm from the door outer panel to prevent contact of the panels

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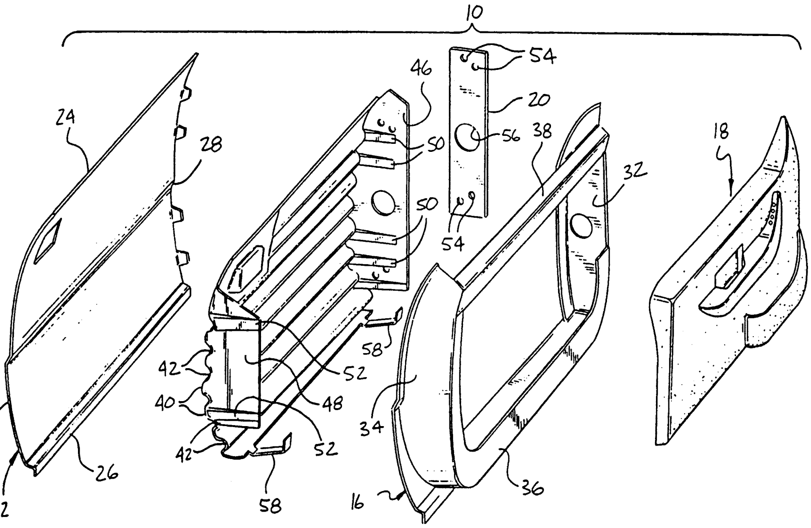


**Fig. 1** (a) Schematic aluminum door construction including a Simplified Total Aluminum Reinforcement'' (STAR) panel (taken from (Ref 8)); (b) vertical door section showing the inner panel, outer panel, and STAR panels

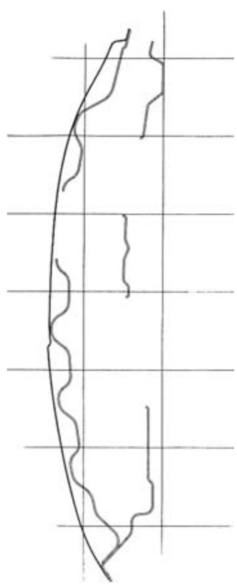

**Fig. 2** Vertical door section showing the inner, outer, and STAR panels

as the result of dimensional discrepancies or normal vibration in service. However, a 1 mm gap (filled with mastic adhesive) was used between the outer panel and the STAR panel at the uppermost corrugation to implicitly define a closed box section that acts as an outer belt line reinforcement (Fig. 2). Similarly, a 1 mm gap and mastic were used together at the corrugation placed directly behind the door molding.

The aluminum inner belt reinforcement was a near copy of its steel door counterpart. Computer modeling indicated that the effectiveness of the reinforcement was nearly insensitive to material thickness. The inner belt reinforcement was consequently developed to match the outer panel thickness of 1.2 mm.

The weld locations at all interface common to the steel door duplicated the steel door design. Performance modeling was used to define the number and location of welds unique to the aluminum door design. Flanges within the window aperture could not be enlarged due to the carryover trim used to cover the flanges. To facilitate welding of the aluminum in the window aperture, local tabs were added to provide a greater landing area for weld gun tips at the weld positions. The tab projections beyond the steel flange widths were then ground off after welding.

Flat hems were used around the periphery of the door to join the inner panel to the outer panel. Quick-plastically formed 5083 aluminum can be flat-hemmed without cracking in the as-formed (annealed) condition. In contrast, conventionally stamped 6XXX alloys used for automotive outer panels are generally susceptible to cracking unless rope (relieved) hems are used (Ref 9, 10).

### 2.2 Material Thickness Selections

Quick Plastically Formed aluminum panels tend to exhibit greater thickness variation than their conventionally stamped counterparts. Material thicknesses for blanks were developed through a two-step process. First, after the initial design surfaces were completed, component models were combined into door system models and are evaluated for standard static and dynamic load cases. Iterative evaluation and optimization were applied to determine average product thicknesses needed in the major panels (Table 1). Next, 2-dimensional forming simulations and engineering judgment were used to determine the initial blank thicknesses needed to achieve the final product thicknesses. The computer simulations actually predicted that the door inner panel blank could be 0.1–0.2 mm thinner than the STAR panel blank. However, in view of the approximations implicit to the selection of appropriate material thicknesses, the blank thickness of the door inner and STAR panels was chosen to be common for these prototype doors.

## 3. Individual panel design features

### 3.1 Front Door Outer Panel

A target panel thickness of 1.2 mm was selected to provide the needed rigidity relative to the 0.8 mm steel outer panel. The

**Table 1 Major panel product thicknesses and blank thicknesses developed from computer aided performance modeling and forming simulations**

| Panel Name | Design Thickness, mm | Blank Thickness, mm | Panel Mass, kg |
|---|---|---|---|
| Front door outer | 1.2 | 1.2 | 3.34 |
| Front door inner | 1.8 | 2.2 | 5.48 |
| Front door STAR | 1.8 | 2.2 | 3.78 |
| Front door hinge reinforcement | 2.5 | 3.0 | 0.55 |
| Front door inner belt reinforcement | 1.2 | 1.2 | 0.11 |
| Rear door outer | 1.2 | 1.2 | 2.97 |
| Rear door inner | 1.8 | 2.2 | 5.05 |
| Rear door STAR | 1.8 | 2.2 | 3.633 |
| Rear door inner belt reinforcement | 1.2 | 1.2 | 0.08 |

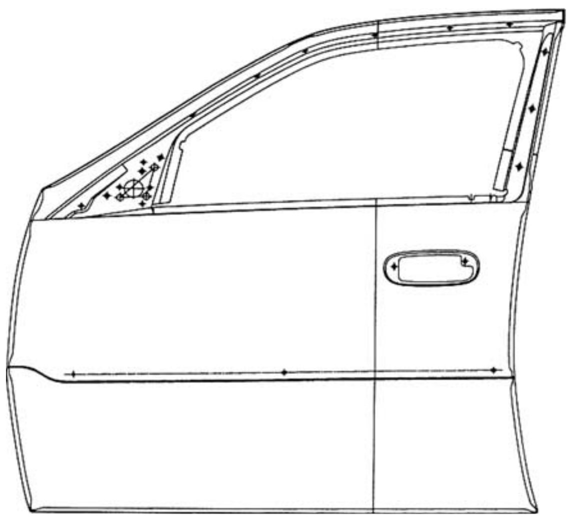

**Fig. 3** Front door outer panel

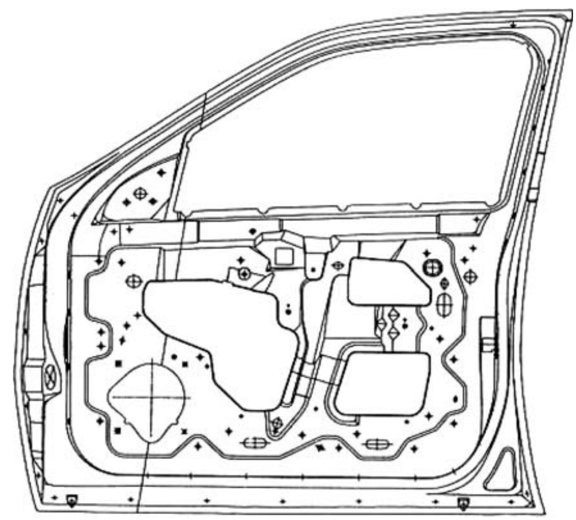

**Fig. 4** Front door inner panel

outer surface geometry of the panel was developed to match the exterior design of the baseline steel door (Fig. 3).

The flanges along the outer periphery of the door were situated in a manner so that they could be hemmed directly from their as-formed positions. In order for the panel to be removed from the form tool, the door panel shape was tipped so that all flanges had positive draft angles relative to a vertical extraction direction. The flanges along the top and bottom of the door were opened to a larger angle (~131° and ~149°, respectively) than those used at the front and rear of the door (~97° for both) due to the tumblehome curvature in the door panel geometry. In defining the final die tip, the panel orientation was biased to provide the smallest possible flange angle at the top of the door. The flange positions chosen for the outer panel could be trimmed readily with a robotic laser system, but would require complex cam-trimming in multiple operations if a conventional trim press was to be used.

The peripheral flange lengths were carried over from the steel panel design without the application of any "plus"-ing to account for the "roll-in" caused by hemming. Consequently, the formed panels were anticipated to be slightly short in the final trimmed and hemmed door-in-white. The weld locations within the window aperture were carried over from the steel door design without any changes. The flanges within the window aperture were nominally maintained at the length used in the steel panel (17 mm), but were increased in size locally to 20 mm at all weld locations.

To maintain the best possible surface quality, the door outer panel was designed to be formed over a male tool with the class-A show surface on the gas side of the tool. Vent holes were placed just above the horizontal feature line in the door where any witness marks on the panel exterior would be covered by the door molding.

### 3.2 Front Door Inner Panel

The front door inner panel largely replicated the steel door inner panel (Fig. 4). The inside (J-plane) surface of the door was maintained identically to the steel door geometry so that the interior trim pad would fit without modification. The seal surfaces were also held constant so that existing seals could be carried over without performance problems. Since the door inboard and outboard dimensions were largely maintained, the additional material thickness of the re-engineered aluminum components was driven toward the center of the door section. This material placement was slightly detrimental to the goal of achieving comparable stiffness to the steel door, because section stiffness could not be used to offset the lower modulus of aluminum. Stiffness was particularly difficult to maintain in the header sections of the door.

A 1 mm-thick extruded aluminum retainer replaced the 0.7 mm-thick steel weather-strip retainer that runs along the top and front header sections of the steel door. The extruded retainer was clinched into place in the aluminum door. All stiffening flanges along the periphery of raised bosses on the door inner panel were replaced by 45° flanges to facilitate laser trimming.

### 3.3 Front Door STAR Panel

The conventional impact beam of the steel door was replaced with a multifunctional Simplified Total Aluminum Reinforcement panel (Fig. 5). For the door-into-roof architecture of the baseline steel door, the original STAR panel concept (Ref 1) was modified in several important respects. To reinforce both hinge and latch areas, the original STAR panel incorporated a closed-box structure that would require a forming tool with moving elements for manufacture. For this program, an open-ended STAR panel was chosen for two reasons. First, the open-end design allows forming in a simpler, single-piece tool. Second, the open-end design provides a slip plane during door assembly, so that a possible interference condition with the inner panel is prevented. Computer modeling indicated that gloving of the STAR to the inner panel would not provide sufficient stiffness to the hinge area to resist check loads, so the front door STAR panel was designed to reinforce the latch area only.

Computer modeling of static and dynamic performance influenced the design of the STAR panel corrugation geometry. Static resistance to crush would be optimized with a set of deep corrugations with sharp corners (Fig. 6a). However, modeling of dynamic performance indicated that a too-strong STAR panel carried the indenting loads to the B-pillar too efficiently. In this prototype program there was no opportunity to alter the body-in-white structure. Consequently, the STAR panel corrugation geometry was weakened until it was designed to just pass static and dynamic crush resistance tests, while not degrading the body performance. The final beam-like corrugations were considerably less severe than the corrugations of previous designs (Fig. 6b), and tapered to become very shallow at the extreme ends of the door. The taper at the rear of the door also allowed packaging of the existing lock rods and glass channel.

The STAR panel was designed for high-volume assembly with traditional assembly fixtures. Two cutouts were introduced to allow fixturing pins to pass through the STAR panel into the inner panel during assembly. The rearward aperture also allowed packaging space and assembly access for the door handle mechanism. Further, the rear apertures provided access to spot-weld the STAR panel to the inner panel at the shut face. The precise geometry of the two cutouts was designed in conjunction with the corrugation pattern to allow the door to meet the static and dynamic performance goals.

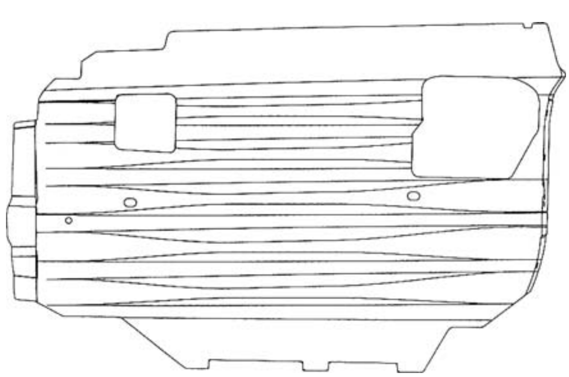

**Fig. 5** Front door STAR panel

The bottom of the STAR panel was joined to the door inner panel with pairs of welds at each of three tabs at the door bottom. The tab geometry allows the STAR and inner panels to be brought together easily for welding, without distorting the paired assembly when small geometry discrepancies occur.

### 3.4 Front Door Hinge Reinforcement

The baseline steel door inner panel had a tailor-welded blank with thick-gage material at the hinge position. At the time of the aluminum door design program, no capability existed to blow-form a tailor-welded aluminum blank. In conjunction with the decision to use an open-ended STAR panel, a decision was made to add a separate front door hinge reinforcement. The hinge reinforcement (Fig. 7) nominally gloves the inner panel geometry. However, most surfaces have been offset locally so that the inner panel and reinforcement only contact each other in the discrete areas needed for function.

### 3.5 Rear Door Outer and Inner Panels

The design of the aluminum rear door outer and inner panels (Fig. 8) incorporated the same considerations discussed above for the front door panels.

### 3.6 Rear Door STAR Panel

The rear door STAR panel (Fig. 9) was designed with the open end facing aft. Because the rear door is shorter, lighter, and contains less hardware than the front door, the hinge face of

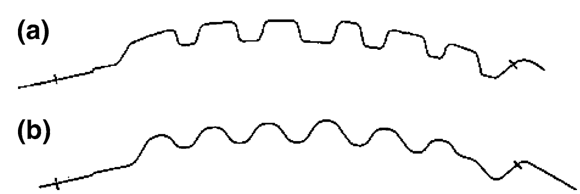


**Fig. 6** STAR panel corrugation geometries: (a) greater impact strength; (b) better formability

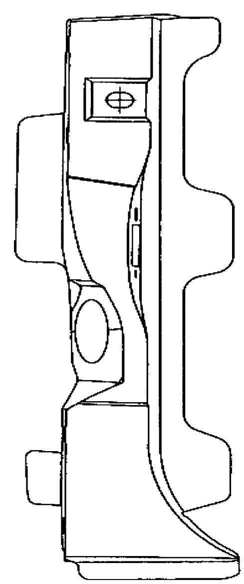

**Fig. 7** Front door hinge reinforcement panel

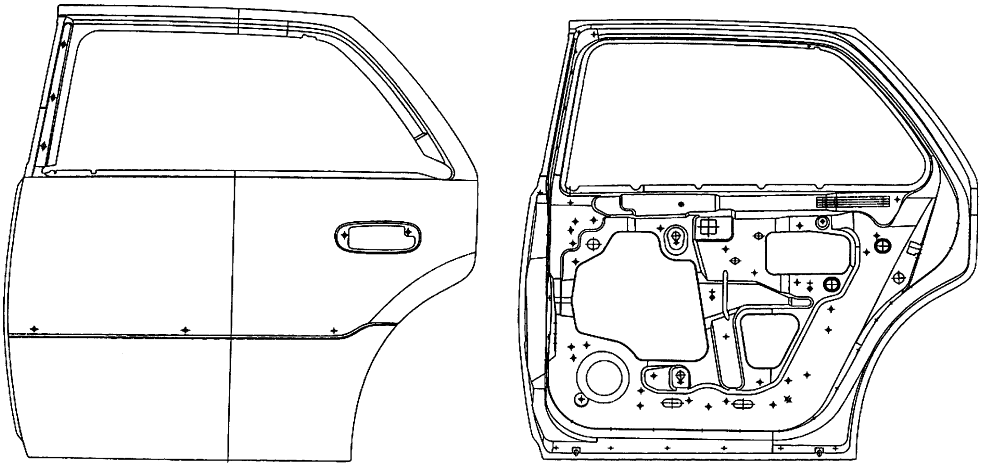

**Fig. 8** Rear door outer and inner panels

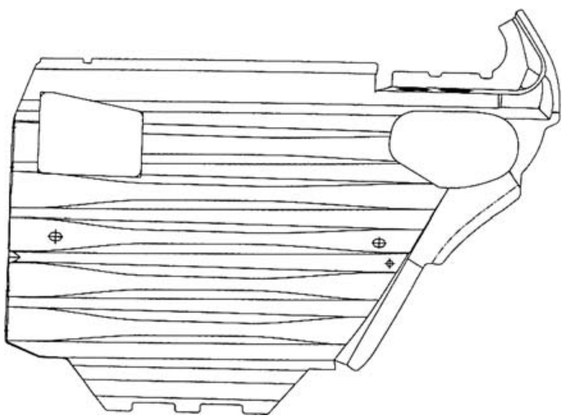

**Fig. 9** Rear door STAR panel

the door can be much lighter and still provide adequate stiffness. The combined thickness of the rear inner- and STAR-panels was sufficient to support the door from the hinges, and consequently the rear door did not require a separate hinge reinforcement. Small aluminum check link and latch reinforcements were added to the rear door to address local loads at those areas. Note that a reinforcement to improve header stiffness was made as an integral part of the rear door STAR panel. The cutouts on the rear STAR panel provided weld access and assembly fixturing capability similar to the front door STAR panel.

## 4. QPF aluminum door design summary and predicted performance

Figure 10 shows exploded views of the front and rear doors, respectively. Table 1 includes a summary of the major aluminum sheet components used in the door-in-white assemblies, along with their masses. The aluminum door designs predicted 5.7 kg of mass savings for the front door, and 5.5 kg of mass savings for the rear door versus their steel counterparts.

Several modeling iterations were used to assess and improve the QPF aluminum door designs. Table 2 contains the computer-predicted linear-elastic displacements and maximum loads for several important load cases. The static elastic modeling used to predict the doors' behavior is only a first order approximation to the actual elastic-plastic deformation behavior that doors exhibit during actual testing. However, such modeling is useful for direct comparison among competing designs. Predicted structural performance figures for the QPF aluminum door designs and the baseline steel prototype door geometries yield differences in qualitative behavior that will likely carry over into real-world structures. The aluminum doors nearly matched the steel doors' characteristics for vertical rigidity, inner and outer belt stiffness, and upper and lower torsion load cases. These areas of performance are expected to be acceptable in actual aluminum doors, even though certain predicted performance measurements (such as belt line stiffness) failed to meet the targets. The upper frames of the aluminum doors were more compliant than the steel doors, particularly at the front of each header. In a clean sheet design approach, these headers could be stiffened by enlarging the header sections, or the seal system itself could be revised.

## 5. Door-in-white build process

All major door panels were formed with unheated tools in a heated press at ~450 °C. Forming cycles were not optimized for production of the prototype panels. Boron nitride was used as a forming lubricant. Formed panels were acid-washed and subsequently trimmed and finished. Panel dimensions were qualified with 3 mm offset check fixtures. Final panel thicknesses remained above 50% of the initial blank thickness throughout each of the formed panels. The average thickness in each panel somewhat exceeded the targeted design thickness of Table 1.

The aluminum doors were assembled with spot welding as the principal joining technique. Straight-acting AC and inverter DC weld guns were used for all welding. Two-inch radiused caps of either 8 or 10 mm face diameter were used.

The inner belt reinforcement (and hinge reinforcement for the front door only) was welded to the door inner panel in an

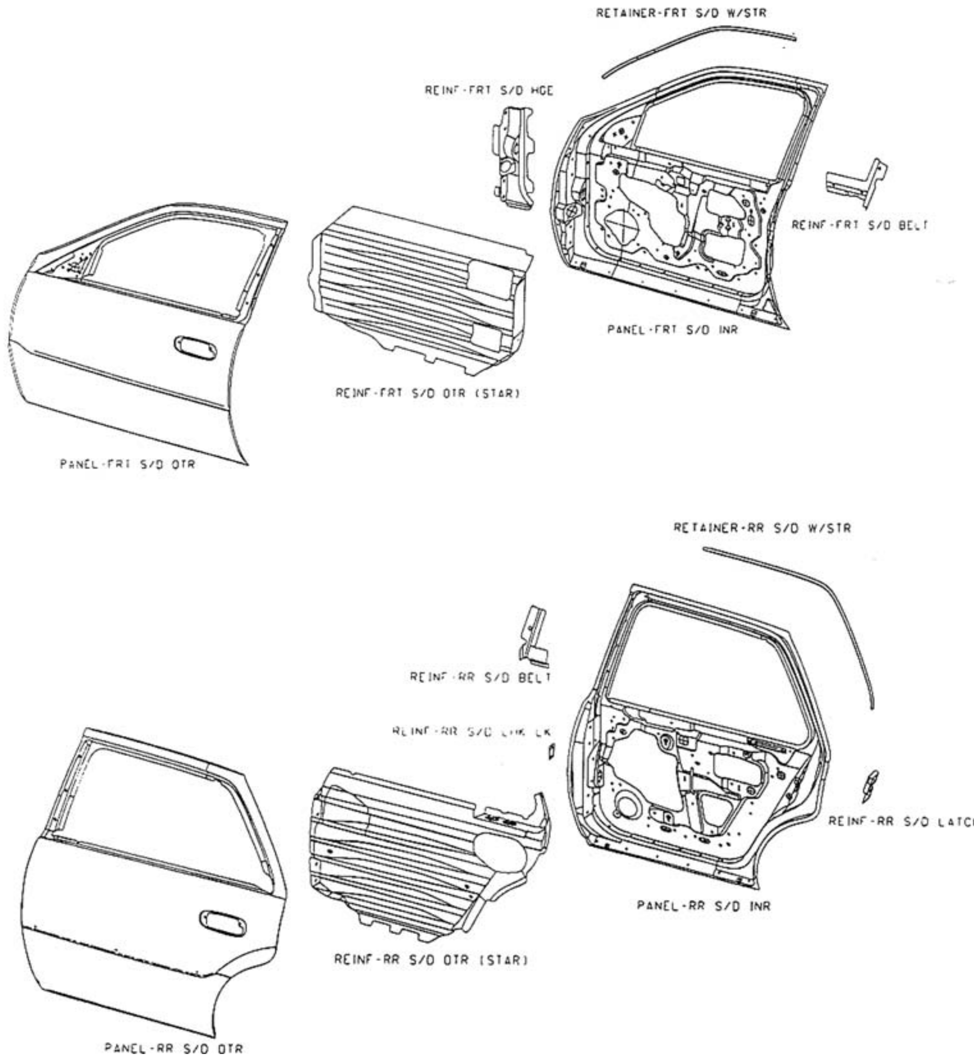


**Fig. 10** Aluminum door construction details

**Table 2 Predicted structural performance for aluminum doors vs. steel prototype doors**

| | Aluminum front door | Steel proto. front door | Aluminum rear door | Steel proto. rear door |
|---|---|---|---|---|
| Vertical Rigidity | 7.44 mm | 6.4 mm | 8.5 mm | 8.4 mm |
| | 280 MPa | 491 MPa | 342 MPa | 537 MPa |
| Inner Belt Stiffness | 8.9 mm | 9.1 mm | 9.9 mm | 11.1 mm |
| | 163 MPa | 579 MPa | 143 MPa | 465 MPa |
| Outer Belt Stiffness | 9.0 mm | 11.8 mm | 7.5 mm | 11.3 mm |
| | 303 MPa | 445 MPa | 183 MPa | 447 MPa |
| Upper Torsion | 2.7 mm | 2.6 mm | 1.4 mm | 2.0 mm |
| | 101 MPa | 372 MPa | 126 MPa | 610 MPa |
| Lower Torsion | 2.4 mm | 3.9 mm | 3.3 mm | 5.6 mm |
| | 106 MPa | 511 MPa | 106 MPa | 512 MPa |
| Upper Frame (Forward) | 18.6 mm | 12.5 mm | 24.1 mm | 13.8 mm |
| | 106 MPa | 209 MPa | 169 MPa | 242 MPa |
| Upper Frame (Aft) | 21.0 mm | 18.4 mm | 12.6 mm | 13.7 mm |
| | 148 MPa | 339 MPa | 82 MPa | 197 MPa |
| Mass | 14.8 kg | 20.5 kg | 13.0 kg | 18.5 kg |

assembly fixture. The inner subassembly was then removed and replaced after the STAR panel was located in the reconfigured fixture for initial welding of the STAR panel. Re-spot welding was done outside the fixture to complete the inner-STAR subassembly. Following the attachment of all the reinforcements to the inner panel, the outer and inner panels were hemmed together in a hem fixture. Finally, the inner panel was joined to the outer panel along the flanges within the window aperture.

Inconsistent welding occurred along the weld flanges during manual welding, particularly around the interior of the window aperture following hemming. Hence, clinches were used for joining within the window apertures of the development doors.

Twelve door-in-white sets were assembled (weld, re-spot, hem, clinch) and then painted. Doors for FMVSS, LINCAP, and durability tests were fully completed with steel door carryover hardware.

## 6. Door validation tests

### 6.1 Static Behavior

Static structural performance of the aluminum doors was quite satisfactory when compared to the performance of baseline steel doors (Table 3). For the front door, all deflection metrics but two met the target values, and each of the two measurements bested the prototype steel door performance. The very large deflection at the upper B-pillar position is consistent with the steel door performance, and can be considered characteristic of the baseline door design (i.e., the header section controlling deflection). Because the aluminum door shared exterior dimensions with the steel door, material thickness increases were driven into the header's closed sections. It is worth noting that the upper frame rigidity at the A-pillar was acceptable in the aluminum door. The aluminum door design did not make use of a tailor-welded blank (as the steel door did) and the additional hinge reinforcement panel used in lieu of the tailor-welded blank did not extend into the mirror patch portion of the door to stiffen the header frame. For the rear door, three deflection metrics failed to meet the targets, but the values were close enough to the specifications that the door was judged to provide adequate real-world performance with little or no modification to the design used.

### 6.2 FMVSS214 Static Side Intrusion

Static door-intrusion tests were run on both front and rear doors (Table 4). The measured loads exceeded the FMVSS 214 requirements. In both doors, the initial load increase was quite steep, in fact, steeper than prototype steel doors (compare Fig. 11 and 12). The test plots are shown in the native units used in the test procedure.

The aluminum door design comprehends the desirability of rapidly developing load resistance early in the intrusion history. A corrugation in the STAR panel located directly behind the molding provides a local hat-section separated from the outer panel by only 1 mm, with mastic in the narrow gap between the panels. Consequently, during displacement by the ram, the STAR panel is loaded almost immediately upon contact between ram and door outer panel.

The maximum loads developed during testing of the doors were exceptional. In fact, one characteristic of the aluminum door tests was that the body side ring, particularly the B-pillar, was displaced to a larger-than-usual extent due to the exceptional stiffness of the aluminum door design.

The protection implied by the resistance to static intrusion suggests that the design could be further optimized to reduce mass. Even greater occupant protection could be provided if the door were designed in synergy with a complimentary body structure from a clean sheet of paper.

### 6.3 LINCAP Dynamic Side Intrusion Test

A full vehicle equipped with front and rear aluminum door was subjected to the LINCAP dynamic side impact test. In light of the greater resistance of the aluminum doors to intrusion, there were concerns that the steel body side structure would not be able to resist excessive deformation during a dynamic side

**Table 3 Structural performance for aluminum doors and vs. steel prototype doors (front and rear doors)**

| Load Case | Target Value | Aluminum front door (test) | Steel prototype front door (test) | Target Value | Aluminum rear door (test) | Steel prototype rear door (test) |
|---|---|---|---|---|---|---|
| Vertical Rigidity | <9.0 mm (<1.0 set) | 8.2 mm (1.4 set) | 6.55 mm (0.83 set) | <9.0 mm (<1.0 set) | 10.3 mm (1.97 set) | 8.2 mm (1.3 set) |
| Inner Belt Stiffness | <6.0 mm (<0.5 set) | 6.1 mm (0.2 set) | 5.18 mm (0.25 set) | <6.0 mm (<0.5 set) | 6.46 mm (0.33 set) | 6.3 mm (0.66 set) |
| Outer Belt Stiffness | <7.0 mm (<0.5 set) | 4.4 mm (0.4 set) | 5.87 mm (0.70 set) | <7.0 mm (<0.5 set) | 3.54 mm (0.14 set) | 3.87 mm (0.30 set) |
| Upper Torsion | <10.0 mm (<1.5 set) | 4.5 mm (0.2 set) | 6.16 mm (1.35 set) | <10.0 mm (<1.5 set) | 3.41 mm (0.38 set) | 5.40 mm (0.68 set) |
| Lower Torsion | <10.0 mm (<1.5 set) | 3.0 mm (0.3 set) | 4.62 mm (0.26 set) | <10.0 mm (<1.5 set) | 3.24 mm (0.23 set) | 4.55 mm (0.12 set) |
| Upper Frame (A-Pillar) | <19.0 mm (<2.0 set) | 16.5 mm (0.6 set) | 13.48 mm (0.99 set) | <19.0 mm (<2.0 set) | 32.8 mm (4.4 set) | 17.8 mm (0.90 set) |
| Upper Frame (B-Pillar) | <19.0 mm (<2.0 set) | 28.4 mm (1.6 set) | 31.22 mm (7.68 set) | <19.0 mm (<2.0 set) | 17.8 mm(1.2 set) | 14.2 mm (0.6 set) |
| Mass | | 12.0 kg | 17.5 kg | | 10.4 kg | 15.5 kg |

**Table 4 Predicted and measured static side intrusion behavior**

| Door | Intrusion | FMVSS214 Regulation | Predicted Load | Test Results |
|---|---|---|---|---|
| Front Door | @ 152 mm | 10.0 kN | 11.1 kN | 11.8 kN |
| | @ 305 mm | 15.6 kN | 25.7 kN | 31.7 kN |
| | Peak load inside 457 mm | 31.1 kN | | 66.7 kN |
| Rear Door | @ 152 mm | 10.0 kN | 13.8 kN | 12.7 kN |
| | @ 305 mm | 15.6 kN | 35.3 kN | 28.8 kN |
| | Peak load inside 457 mm | 31.1 kN | | 59.8 kN |

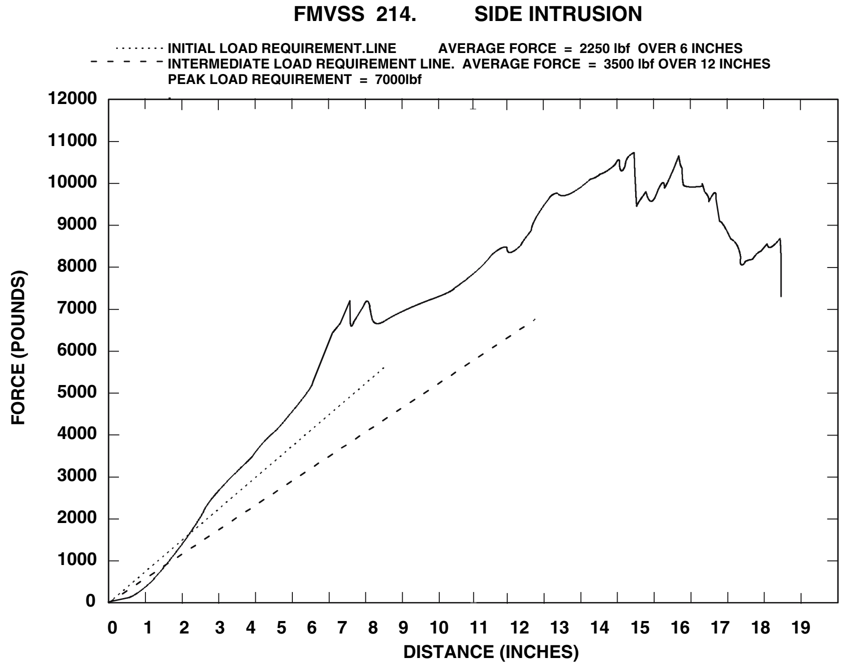


**Fig. 11** FMVSS214 static intrusion behavior for baseline steel front door

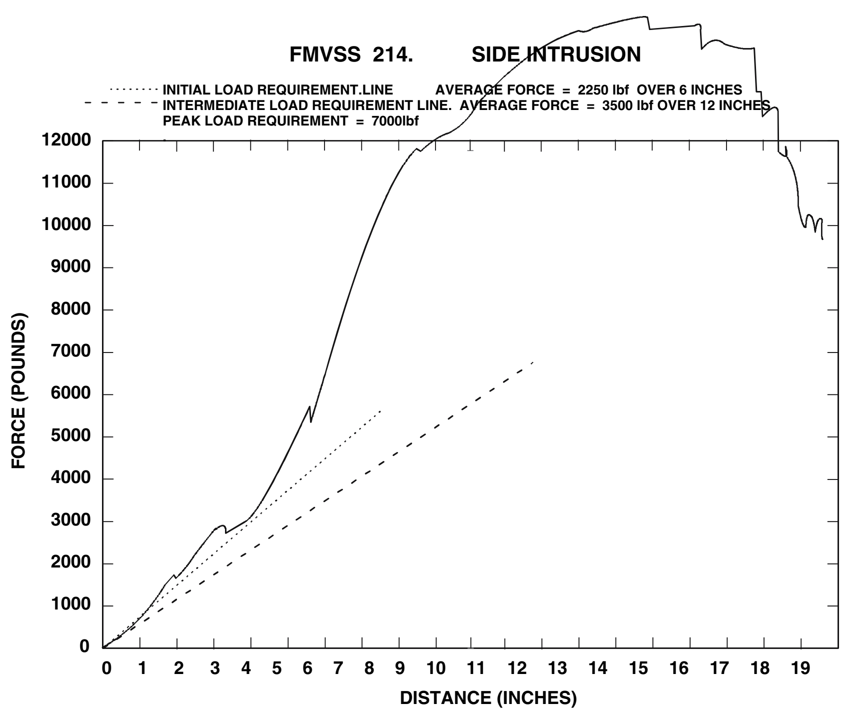


**Fig. 12** FMVSS214 static intrusion behavior for aluminum front door

impact event. Recall that the body structure was not designed for the aluminum doors; the aluminum doors were simply placed in the existing steel structure. Analysis predicted that with the QPF aluminum doors in place, the B-pillar displacement would exceed that of the steel door test by 28%. Further, the load transfer pattern differed between the steel and aluminum doors. In the case of the steel door, the load transfer is concentrated at the ends of the tubular reinforcement beam. For the case of the aluminum door, the STAR panel distributes the load along the entire periphery of the door below the beltline, with the net load transfer occurring higher at the A-, B-, and C-pillars.

Results from the LINCAP test showed that occupant protection was satisfactory for the aluminum doors. The Thoracic Trauma Index number was similar to that for the steel door test. Pelvic accelerations were lower for the aluminum door test. The Side Impact Sensor (SIS) fired more slowly before deploying the side air bag, as predicted by previous analysis. This condition results from the position of the SIS, which was optimized specifically for the concentrated loads generated at the end of the door beam used in the steel door.

Both the body side and air bag systems could be re-engineered to provide more occupant protection in a vehicle fully engineered for the QPF aluminum doors. It is notable that even in the absence of such optimization, the steel body equipped with the aluminum doors provided acceptable occupant protection.

### 6.4 Long Term Durability Testing

Both front and rear aluminum doors were subjected to standard long-term door slam tests. After five lives of testing, neither door developed any fatigue cracks or weld separations.

## 7. Implications of validation test results

The QPF aluminum doors substantially passed all the performance metrics for an automotive door. Areas that might be improved in a clean sheet design include:

(1) Increased header rigidity (by designing for increased header section);
(2) Improved STAR panel geometry (the large holes introduced to allow access for welding could be eliminated if weld access could be obtained through the inner panel);
(3) Reduced door mass (the structural performance of the door was substantially better than a steel door for many load cases, which suggests that the aluminum door panels could be downgaged significantly).

The performance behavior of the aluminum doors is dominated by the STAR panel design. Further development of the STAR panel corrugation pattern and the interfaces of the STAR panel to the door inner and outer panels could lead to even better performance for lower mass in a new door design. A design study indicated that (when packaging considerations allow it) deeper corrugations could substantially reduce the mass of a door system.

## 8. Conclusions

1. Front and rear aluminum doors were designed with single-piece inner panels. Those components could not have been conventionally stamped from aluminum, but were manufacturable with quick plastic forming technology. Other door features enabled by the QPF technology were formed-in flanges and flat hems.
2. The Simplified Total Aluminum Reinforcement (STAR) panel concept used previously in prototype doors for hardtop vehicle architectures was modified for use in the door-into-roof architecture.
3. In the front door, a substantial hinge reinforcement was required to fulfill the function of the thicker portion of the tailor-welded blank used in the steel door.
4. Certain criteria were applied in developing the aluminum doors for an existing body structure and packaging envelope that prevented the doors from being fully optimized. A "clean sheet" approach to a new vehicle would likely provide even lighter doors with still better structural performance.
5. Front and rear doors were constructed from quick plastically formed aluminum panels. Spot welding was used for the majority of joints, but clinches were used selectively where welding was difficult. The use of clinches was limited to the inner/outer joint within the window aperture, and the joint between the inner panel header and the weather-strip retainer.
6. The QPF aluminum doors-in-white exhibited mass savings of 5.1 kg/front door and 4.7 kg/rear door (19.6 kg/vehicle) versus their production steel counterparts.
7. Front and rear aluminum doors exhibited static stiffness behavior nearly on par with steel doors. Upper header rigidity was lower than that of the steel doors due to the low elastic modulus of aluminum. Computer predictions of elastic behavior based on the design model were reasonably good, but indicated somewhat poorer performance than that actually obtained in the prototype doors.
8. The static intrusion resistance of the aluminum doors significantly exceeded the requirements of the applicable standard for side doors.
9. The aluminum doors passed the dynamic side-impact test. Composite thoracic accelerations were similar to those accompanying tests of the steel doors, but the aluminum doors provided slightly better protection at the pelvis position.
10. Door slam durability tests were carried out to 5 lives. Both front and rear doors survived with no loss of function.
11. Overall performance of the prototype QPF aluminum doors indicates that they were suitable for application in an automotive structure.


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