The Synergy™ Door – A New Approach to Lightweight Steel Doors

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Outline

• Background
• Approach
• Structural Performance Targets
• Synergy™ Door Concept, Performance, Cost
• Adhesives Investigation
• Summary and Conclusions
• **Challenge:** to design a steel door to meet OEM’s demands for lightweighting of the vehicle.

• **Constraints:**
  - Use reasonable but leading edge steel grades and gauges, currently available.
  - Parts are “makeable” and “weldable” with today's technologies.
  - For example, outer panel using 0.50 - 0.60 mm DP490 exposed quality.

Incremental aluminum weight savings economically unattractive to OEMs

Cost neutral or small acceptable penalty

Good structural performance
Synergy™ Lightweight Steel Door: Innovative Concept

- Clean sheet design - 3G (Geometry, Grade, Gauge) optimization considering 6 load cases simultaneously
- Revolutionary, not evolutionary design concept
- Matches aluminum mass at ~ 30% lower cost
- Uses structural adhesives
- Concept can be applied to open or closed inner designs
- All grades and gauges currently available
- Patent applied for

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**SCHURTER e*t al.**

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USPC 2013/008,837 A1

**ABSTRACT**

A vehicle door assembly comprises an inner panel integrally formed by upper and lower horizontal beams interconnected by front and rear U-shaped side frame members non-detachably attached to each other by upper and lower intermediate frame members so as to form a continuous perimeter. The side frame members are made of a first steel material and the intermediate frame members made of a second steel material, which is different from the first steel material. A method for manufacturing the inner panel comprises the steps of providing U-shaped sheets of the first steel material, providing top and bottom sheets of the second steel material, non-detachably connecting the U-shaped sheets to the top and bottom sheets so as to form a blank, and stamping the blank into the frame position.
Baseline D-segment Production Door
(Structurally Efficient)

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Thickness</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer panel</td>
<td>BH180</td>
<td>0.75 mm</td>
<td>4.502 kg</td>
</tr>
<tr>
<td>Hinge reinforcement</td>
<td>HSLA340</td>
<td>1.75 mm</td>
<td>1.965 kg</td>
</tr>
<tr>
<td>Inner panel</td>
<td>ArcelorMittal 05</td>
<td>0.8 mm</td>
<td>3.962 kg</td>
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<tr>
<td>Upper hinge reinforcement</td>
<td>HSLA340</td>
<td>3.0 mm</td>
<td>0.123 kg</td>
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<tr>
<td>Lower hinge reinforcement</td>
<td>HSLA340</td>
<td>3.0 mm</td>
<td>0.144 kg</td>
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<tr>
<td>Side impact beam</td>
<td>MSW1200</td>
<td>1.6 mm</td>
<td>1.838 kg</td>
</tr>
<tr>
<td>Outer panel upper stiffener</td>
<td>ArcelorMittal 04</td>
<td>0.65 mm</td>
<td>0.190 kg</td>
</tr>
<tr>
<td>Window guide</td>
<td>ArcelorMittal 04</td>
<td>0.8 mm</td>
<td>0.169 kg</td>
</tr>
<tr>
<td>Mirror bracket</td>
<td>HSLA340</td>
<td>1.0 mm</td>
<td>0.180 kg</td>
</tr>
<tr>
<td>Waistline door beam</td>
<td>HSLA340</td>
<td>1.00 mm</td>
<td>0.550 kg</td>
</tr>
<tr>
<td>Front window frame reinforcement</td>
<td>HSLA340</td>
<td>1.00 mm</td>
<td>0.390 kg</td>
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<tr>
<td>Rear window frame reinforcement</td>
<td>HSLA340</td>
<td>1.00 mm</td>
<td>0.560 kg</td>
</tr>
<tr>
<td>Latch reinforcement</td>
<td>HSLA340</td>
<td>0.8 mm</td>
<td>0.048 kg</td>
</tr>
<tr>
<td>Window guide</td>
<td>ArcelorMittal 04</td>
<td>0.8 mm</td>
<td>0.190 kg</td>
</tr>
<tr>
<td>Mirror bracket</td>
<td>HSLA340</td>
<td>1.0 mm</td>
<td>0.180 kg</td>
</tr>
</tbody>
</table>

Mass 14.64 kg
Approach

- Taking weight out of the door is tough!
  - ≈ 80% of the door-in-white (DIW) weight is accounted for in only 4 parts - the outer panel, the inner panel, the hinge reinforcement (either as a separate part or a LWB to the inner), and the side impact beam.
  - If we constrain ourselves to the traditional door architecture, then design efforts are focused on these 4 parts.

- A clean sheet approach is necessary for significant weight savings.
3G Optimization Methodology

FEA of the Baseline

Designable Volume

Topology Optimization

Parameterized Model

3G Design Optimization

Baseline Calibration

Design Space Definition

Primary Design Envelope

Parameterized Design Envelope

Optimized Design

Concept Design

**14.6 kg**
Define structural targets / requirements.

Maximize design freedom:
Account for window drop.
“Check” for all other hardware.

Load path studies, defining important structures from topology.

Define and parameterize door structure.

**7.8 kg**
Theoretical minimum weight door disregarding manufacturing and material constraints.

**10.5 kg**
Considering manufacturing and material constraints.

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**Parameterized Design Envelope**

**Main Structural Sub-systems of RAW Topology Model Loadpath Mapping**

- Header Rigidity
- Beltline Rigidity
- Torsion Rigidity
- Door Sag
- Door Overload
- FMVSS214

Percentage of Total Loadcase Force

- 0%
- 2%
- 4%
- 6%
- 8%
- 10%
- 12%

Defined and parameterized door structure.

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**ACP**

**eta**
Parameterized model

Beams can translate

LWB lines can translate

Cross Sections can change shape and size within defined package space
Door Performance Targets (D-segment)

Crash load case

Side impact FMVSS214S
- Imposed displacement
- Pole impactor 450 mm/80 ms
- Requirements
  → At 152 mm >10kN
  → At 304 mm >16kN
  → At 457 mm >37kN

Door Beltline beam
- Load path
- Sub system model
- Imposed displacement
- Requirements
  → Peak > 60kN

Door Sag
- Load: 1000 N at the handle
- Requirements
  → Max disp.: 2 mm
  → Residual disp. < 1 mm

Wind Overload
- Load: 400 N
- Requirements
  → Max opening: 6 deg.
  → Residual opening < 1 deg.

Torsion Stiffness
- Load: 100 N-m couple
- Requirements
  → Min Target: ≥ 326 N m / deg

Beltline Squeeze
- Load: 200 N
- Requirements
  → Max disp.: 3 mm
  → Residual disp.: none

Frame Stiffness
- Load: 200 N (applied separately)
- Requirements
  → Max disp.: 5.2 mm
  → Residual disp.: none

Oil Canning
- 75 mm dia. Disk.
- Requirements
  → ≤ 4 mm deflection at 90 N load

Also ≈ > 55 Hz modal requirement
Module extension replaces the traditional inner, but is less than half of the normal draw depth. Bonding of the inner structure to the outer eliminates the need for a traditional impact beam.
Synergy™ Door Concept: Design Highlights

• Multi-functional **inner structure**, important for static load cases and side intrusion.
Synergy™ Door Concept: Design Highlights

Inner window frame extends into the inner “picture frame” for better stiffness
Synergy™ Door Concept: Design Highlights

• Efficient door requires active structures outside of the glass drop just inside of the outer panel.

• Structural efficiency is improved by **adhesively bonding the inner structure to the outer skin**. The outer serves a structural purpose beyond just providing dent resistance and weather protection (outer panel and inner structure perform **synergistically**).

• The entire inner can resist intrusion thereby eliminating the traditional impact beam.

• Optimization identifies **Usibor® 1500P** and **LWBs** as key enablers for a lightweight door solution.
Synergy™ Door Concept: Design Highlights

Vertical Beam: 0.6 mm, Usibor® 1500

Waistline Beam:
- 0.6 mm, Usibor® 1500

Module Extension:
- 0.5 mm, DP490

Hot Stamped “picture frame”:
- 0.6 mm, Usibor® 1500

Gusset Beam: 0.6 mm, Usibor® 1500

Window Frame Inner and Outer:
- Inner Frame, Laser welded blank: 0.76 / 0.60 mm, DP490
- Outer Frame, Laser welded blank: 0.55 mm, DP490 / 0.60 mm, DP980

Hinge Assembly:
- 0.6 mm, DP600
- 1.5 mm, DP980
- 3.5 mm, DP980 Washers

Weight:
- 10.5 kg
- - 4.1 kg (-28%)

Outer Panel: 0.55 mm, DP490

Tensile strength values:
- PHS ≥ 1300 MPa
- AHSS ≥ 1180 MPa
- AHSS ≥ 900 MPa
- AHSS ≥ 780 MPa
- AHSS ≥ 590 MPa
- AHSS ≥ 450 MPa
- HSS
- Mild Steel

Adhesive length = 3216 mm
The entire inner structure resists intrusion thereby eliminating the traditional impact beam.

FMVSS static side intrusion
Average Force 2442 lbf vs. target 2250 lbf in first 6 in.

Note: Adhesive properties and Usibor® 1500 fracture are modeled (no fracture observed).
# Synergy™ Door Concept: Structural and Weight Performance*

* With BETAMATE 18XX adhesive

<table>
<thead>
<tr>
<th>Performance Results</th>
<th>Synergy™ Door</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STATIC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Door Sag</td>
<td>[ ]</td>
<td>1.5 mm (door only)</td>
</tr>
<tr>
<td>Wind Overload</td>
<td>[ ]</td>
<td>3.8 deg. opening</td>
</tr>
<tr>
<td><strong>STIFFNESS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torsional Stiffness</td>
<td>[ ]</td>
<td>500 Nm / deg rotation</td>
</tr>
<tr>
<td>Mid position Frame Stiffness</td>
<td>[ ]</td>
<td>4.9 mm</td>
</tr>
<tr>
<td>Rear position Frame Stiffness</td>
<td>[ ]</td>
<td>3.0 mm</td>
</tr>
<tr>
<td>Beltline Stiffness</td>
<td>[ ]</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>First Mode</td>
<td>[ ]</td>
<td>54.1 Hz</td>
</tr>
<tr>
<td><strong>CRASH</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FMVSS214S Side Impact</td>
<td>[ ]</td>
<td>2442 lbf (first 6 inches only)</td>
</tr>
<tr>
<td>Dent Resistance</td>
<td>[ ]</td>
<td>133 lbf</td>
</tr>
<tr>
<td>Oil Canning</td>
<td>[ ]</td>
<td>4.0 mm @ 90 N Load</td>
</tr>
</tbody>
</table>

**Weight:** - 4.1 kg (- 28%)  
**10.5 kg**

**Performance Ratings**
- Above target ❌
- Close /below target ☑
- Close /at target ☑
- Below target ❌

* With BETAMATE 18XX adhesive
Synergy™ Door Concept Costs

Note: Material cost inputs as of July 2013

Cost penalty of aluminum door: 
~ $10 per kg saved

Cost penalty of Synergy™ Door: 
~ $3 per kg saved

Baseline: 14.64 kg
Synergy™ Door: 10.5 kg

Annual Production Volume = 200,000 vehicles/year
Adhesives Investigation
Adhesive Portfolio

Selection Considerations
- Assembly requirements
- Substrates bonded
- Substrate coatings
- Cure profile
- Functional performance
- Body shop, trim shop
- Manufacturing process

PU Sealants *(BETATECH™ / BETAFILL™)*

PU & Rubber Based Adhesives & Sealants *(BETASEAL™/BETAMATE™/BETALINK™)*

Semi Structural PU Adhesives *(BETAFORCE™)*

Structural PU Adhesives *(BETAFORCE™)*

BETAMATE FLEX

Epoxy Adhesives *(BETAMATE™)*

Elongation (%) vs. Lap shear strength (MPa)
FMVSS 214S Sensitivity Studies
Effect of Elastic Modulus*

Shows synergistic effect of bonding inner structure to outer skin.

* Adhesive failure initially not accounted for in the simulation studies; is addressed later.
Adhesive Coupon Level Studies

Substrate thickness
- DP490 0.68 mm
- USIBOR 1500 1.56 mm

Results
- Lap-shear strength of similar material substrates bonding directly related to bulk adhesive mechanical properties, BETAMATE 73305 > BETAMATE 14XX > BETAMATE 18XX
- Low modulus BETAMATE 18XX shows superior performance for T-Peel, WIP, and lap-shear strength for dissimilar material substrate testing, while minimizing the risk of read through.
Vertical Beam Stability Evaluations

Brittle adhesive
BETAMATE 73305 (high modulus)

BETAMATE 14XX (med modulus)

BETAMATE 18XX (low modulus)
Sensitivity of Adhesive to FMVSS 214S (Considering Cohesive Failure)

- **BETAMATE grades**
  - Tensile properties of BM73305 > BM14XX > BM18XX

- **Key conclusions**
  - Without BETAMATE adhesives, FMVSS 214S side impact requirement is not met.
  - **BETAMATE 73305** is not able to provide sufficient ductility, vertical door beam flange separates from door outer skin (cohesive failure).
  - **BETAMATE 18XX** shows that it can provide sufficient strength in meeting the FMVSS 214S requirements; performs better than the other two adhesives considered.
  - Confirms that the outer skin serves a structural purpose and performs synergistically with the inner structure to resist side intrusion.
Large Panel Adhesive Read Through Evaluations

- Large sheet panel testing
  - Panels 700 mm x 1100 mm x 0.50 mm DP490 GA
  - Hat sections (0.60 mm mild steel)
    - Height = 40 mm
    - Width = 50 mm, 100 mm, and 200 mm
    - Flange = 15 mm
  - Fixture used to establish a reference surface for scanning prior to and after adhesive cure
  - Bond Line Thickness (BLT) 3.0 mm (worst case scenario)

- Test measurements
  - Air oven temperature
  - Sheet metal surface, and adhesive temperature
  - Optical scans
    - Prior to heat exposure
    - After heat exposure, at Room Temperature
  - Real-time 3D surface scan
Large Panel Read Through Evaluations

**BETAMATE 73305 (high modulus)**

Curvature fringe plot $\text{mm}^{-1}$

Visible threshold is a change in curvature of $2.0\times10^{-4} \text{ mm}^{-1}$

No observable curvature pattern for low and medium modulus adhesives after curing.

**BETAMATE 18XX (low modulus)**

**BETAMATE 14XX (med modulus)**
# Synergy™ Door concept: Summary

<table>
<thead>
<tr>
<th>Criteria/issue</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural performance</td>
<td>Good</td>
</tr>
<tr>
<td>Dent resistance and oil canning</td>
<td>Good</td>
</tr>
<tr>
<td>Feasibility – hot stamped</td>
<td>Good (isothermal simulation, T=600 deg C)</td>
</tr>
<tr>
<td>Weld stackups</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Assembly sequence</td>
<td>Completed</td>
</tr>
<tr>
<td>Cost estimation</td>
<td>Completed</td>
</tr>
<tr>
<td>Final design concept geometry</td>
<td>FEA mesh models and rough CAD available</td>
</tr>
<tr>
<td>Adhesive selection</td>
<td>Completed</td>
</tr>
</tbody>
</table>

**Weight:**

- **10.5 kg**
- **Completed**

- **4.1 kg** (28%)
Key Conclusions

- 3G optimization yielded a unique design concept
- Additional structure between outer skin and glass drop
- Adhesive bonding enables synergistic interaction of outer skin with the new inner structure
- Outer skin now serves structural purpose
- Adhesive characteristics achieve structural requirements while mitigating the risk of read through
- Mass approximately equivalent to aluminum
- Cost penalty of $3.00 per kg saved vs. $10.00 per kg saved for aluminum
- Concept can be applied to open or closed inner designs
- All materials commercialized or ready for commercialization
- Collaboration enabled this advancement in technology
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