Lightweight, package and performance improvements of a shock tower by using steel–aluminium hybrid-casting technique

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Abstract
In this work, a shock tower of a mid-size vehicle using steel (St)–aluminium (Al) hybrid-casting technology was developed with current shock towers as a benchmark. The use of this hybrid-casting technology, which features a ductile material connection between steel and cast aluminium, makes it possible to combine the design advantages of cast aluminium with the mechanical properties of high-strength steels. Based on this combination, a new shock tower concept was developed that offers advantages over the state of the art in terms of package, weight, stiffness and crash performance. To develop the new shock tower, connection points and package spaces in the periphery of the Honda Accord MY 2011 were analysed and defined. Based on quasi-static misuse load cases and topology optimization, it was possible to develop a load-compliant rib structure for the hybrid-cast shock tower reinforced by steel in the dome area. A so-called tension band for the IIHS small overlap crashworthiness evaluation test (SOL) was also integrated into the new shock tower to ensure homogeneous load distribution. The new shock tower was tested virtually in comparison with the reference steel shock tower and an Al-cast shock tower in quasi-static and dynamic crash load cases. In the quasi-static test, the hybrid-cast shock tower showed significantly increased stiffness. In the dynamic load cases, a significant overall homogenization of force distribution on the existing load paths in die front body structure was achieved. In addition, 5 mm package space for spring and damper could be gained for better driving behaviours of the car.

Keywords Steel-aluminium hybrid-casting · Lightweight shock tower · SOL · Tension band · Small overlap

1 Introduction and the state of the art

The reduction of vehicle mass through lightweight design of both body and chassis areas is of great importance; 100 kg weight saving may reduce 0.3 l gasoline consumption of vehicle with combustion engines [1, 2] or extend the driving range of a battery-electric vehicle by 4% in case of urban traffic [3, 4]. As is generally known; the pure substitution of steel materials by light metals to obtain a lightweight design is not effective because many other constraints, such as package, comfort, safety and noise-vibration-harshness (NVH) behaviour, must also be fulfilled. A preferred method to meet the conflicting goals of these various requirements is the use of multi-material designs.

Multi-material design in body structures can be realized by using different steels and aluminium alloys. In the mid-size segment, steels are the main choice. If used at all, aluminium (Al) is chosen only for specific components, such as crash management systems. Al-intensive bodies are much more common in the luxury class segment [5], with high-strength steels used in areas subject to particularly high loads. In this category of vehicles, aluminium cast components are also increasingly being used, especially in body areas with high stiffness requirements and parts/functional integrations, such as body structure nodes or chassis connection nodes [6]. Examples of aluminium use include the shock towers of various vehicle models in the upper mid-class (Audi A4 B9, Mercedes-Benz C-Class W205), and luxury class can be found in [5, 7].

Applications like those in [5, 7, 8] show the use of Al castings in local areas of a vehicle structure, such as gussets and chassis connections. In [9], it is demonstrated that a large part of a rear vehicle structure can be manufactured

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The general advantages of aluminium casting are its properties of low weight, adequate strength and stiffness, and a very high freedom of shaping. With cast aluminium components, the material distribution can be adapted to homogenize the load by means of load-optimized rib designs and varying wall thicknesses. However, cast aluminium components generally require more package space than comparable assemblies made of steel since the E-modulus is only 1/3 of steel although the specific weight is also 1/3. Therefore, as already stated, they are almost exclusively used as part of multi-material designs in the luxury class, which can provide this package space [5].

The complex and cost-intensive joining technology (a combination of riveting and adhesive bonding) required to connect cast aluminium components to the usually steel-intensive body periphery is also a reason why this technology has found only little acceptance in the large-scale production of small- and mid-sized cars.

To eliminate the disadvantages of aluminium casting in terms of package space and joining technology, hybrid-casting technology was developed in [10, 11], by which steel inserts can be integrated into aluminium casting in such a way that a high strength and ductile material bond could be established.

### 1.1 Hybrid-casting technology

The basic idea of hybrid-casting technology is to integrate steel inserts into the Al casting parts during the Al casting process. The principles are shown in Fig. 1. In case of Fig. 1a), a part of the steel insert is cast by Al and another part is outside of Al cast, which can be used as a joining flange for spot welding. If the steel inserts are cast inside of Al, it may work as a reinforcement (see Fig. 1b).

### 1.2 Shock tower

The shock tower makes up part of the front wheel housing and is the counterpart to the part investigated in [18]. Its purpose is primarily to withstand the reaction forces of the spring and damper of the front suspension, and it is usually attached to the upper front rail and the major (or middle) front rail.

The mechanical requirements on the front shock towers are highly complex. First, as the load-carrying points...
between the suspension and the body, front shock towers should be designed to be as stiff as possible for the best driving dynamics [6]. Strength is also crucial, as misuse load cases from various driving manoeuvres must cause no plastic deformation in the component. Finally, fatigue strength with respect to cyclic loads from the chassis is also an important mechanical criterion in the design and dimensioning of this component.

The package space of the shock tower also has direct influence on possible spring and damper dimensions (length and diameter) and their characteristics, which in turn have decisive influence on driving dynamics and comfort. The lesser package space taken up by the shock tower in the vehicle’s z-direction, the longer the spring/damper can be. Thus, more design options for spring and damper can be offered.

In addition to the above-mentioned requirements, the shock tower must act as a connecting link between the upper and middle front rails and be placed in an area indirectly relevant to a potential crash. The upper front rail, which is connected to the shock tower or may be part of the shock tower, acts as part of a load path in a frontal crash, transferring forces in the direction of upper and lower A-pillar and can itself deform in a defined way [19]. The properties of the materials play an important role in shock tower’s performance in case of crash events. Shock towers made of steel can naturally deform and absorb energy better than shock towers made of cast Al, which is comparatively brittle and has a lower fracture elongation than the steel materials.

According to [20], the shock tower can play an crucial rule in crash load cases with low overlap between vehicle and barrier, such as the IIHS small overlap crashworthiness evaluation test (IIHS SOL) [21], as it is almost the only link between upper and middle front rails. The IIHS SOL is a challenging test in terms of intrusion into the passenger cell, as the middle front rail, a key component for energy absorption in a vehicle’s front structure, often cannot act as a load path due to the small overlap of 25% between barrier and vehicle [20, 22] (see also Fig. 2b). Instead, the crash load must be carried by the chassis components (such as subframe and trailing arms), wheels and the upper front rail (see Fig. 2a) which is in general short in length and may not carry higher forces. The intrusion into the body cell is thus very high, and doors cannot be opened as well.

To reduce the body cell intrusion and structure damage, in [23–25] several ideas were proposed as patent applications, where a steel tension band (see Fig. 2b) connects the middle and upper front rails. Through this tension band, the crash load of IIHS SOL crash should be transmitted from the upper front rail to the middle front rail, when the tension band is integrated into the shock tower to realize this connection. By retracting the middle front rail to absorb energy, SOL crash behaviour as a whole and, in particular, intrusion into the passenger cell should be improved.

The above-mentioned, varying requirements have led to the development of different designs for vehicles on the market. In the scope of this work, a benchmarking of the current

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Fig. 2  a Load path for IIHS SOL in a vehicle without special design for this load case and  b using a tension band to transfer part of the forces in upper front rail to middle front rail

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shock towers of five mid-size vehicles was carried out. This revealed the various advantages and disadvantages of sheet steel and cast aluminium designs.

Figure 3 shows an example of an assembly of a steel-sheet shock tower, including its periphery, which has relatively little space restriction for the spring/damper package due to its low material thickness of 0.8–1.7 mm in the dome area. The shock tower can be joined directly to the surrounding body-in-white (BIW) components by spot welding.

In comparison, Figs. 4 and 5 show examples of cast aluminium designs with material thicknesses of 2.5–7.5 mm in the base body and 2–8 mm in the ribs. Furthermore, Fig. 4b with internal ribs and Fig. 5a with external ribs show different approaches to the rib structure, which have a direct influence on the space available for spring and damper. In the variant shown in Fig. 4b, the diameter of the installation space of the spring/damper package is restricted by the internal ribs. The outer ribs of the variant shown in Fig. 5a restrict the length of the spring/damper package due to the additional height in vehicle’s z-direction. Both cast aluminium variants have in common that additional joining elements (steel connecting plates) must be introduced for spot welding of the cast Al part to other adjacent steel parts of BIW (for example upper front rail). These steel connecting plates (see Figs. 4c und 5c) are attached to the flange areas of cast Al part using self-piercing riveting and adhesives.

![Fig. 3](image1.jpg)

**Fig. 3** Wheel installation with shock tower in sheet metal design from **a** outside and **b** inside of the car

![Fig. 4](image2.jpg)

**Fig. 4** Detailed images of a cast aluminium shock tower with internal rib structure from **a** outside and **b** inside, as well as **c** example of a steel connecting plate which is joined to aluminium cast part by using rivets and adhesive bonding
2 Target of the current work

As mentioned in Chapter 1.2, shock towers can be assigned the following three main requirements, which significantly determine their design:

1. high stiffness and strength requirements for driving dynamics and comfort
2. largest package space possible for the spring/damper package for driving dynamics and comfort
3. fulfilment of crash requirements, particularly for load cases with small overlap

When lightweight design, structural integrity and functional integration are considered, further requirements can be added to the three above but will vary depending on the vehicle category or manufacturer.

Requirements one and two are in direct competition with each other and result in a conflict of objectives. To achieve the highest possible stiffness and strength, high wall thicknesses and — depending on the design or material used — rib structures are required, particularly in the area of the shock tower top. However, high wall thicknesses and rib structures restrict the possible package space for the spring and damper. Steel structures have the advantage of requiring lower wall thicknesses due to the higher elastic and strength properties of the material and can therefore provide more package space. The use of steel can therefore help strike a balance between requirements 1 and 2. However, the weight of steel part is larger.

Cast aluminium designs offer advantages for lightweight design and functional integration. However, their higher wall thicknesses and rib structures restrict the package space, and they are also inferior to steel structures in terms of crash requirements due to their comparatively brittle behaviour.

When considering hybrid-casting using steel as reinforcement and connecting plate, both directly casted in the Al part during hybrid casting process, the above-mentioned conflicting requirements and requirement for assembling Al part with other steel BIW parts can be solved. The respective advantages of the steel- and Al-cast designs can be unified, and the disadvantage compensated.

The first objective of this work is thus to develop a steel (St)-aluminium (Al) hybrid-cast shock tower with a steel insert in the upper area of the shock tower to reinforce the Al-casting structure at lower thickness. More installation space compared to a pure Al-cast design can be gained due to the reduction in the number or the thickness of ribs and lower wall thickness of the Al-cast material. For this purpose, an existing steel shock tower was first analysed as a reference, and an Al-cast and a St-Al hybrid-cast shock tower were then designed. The performance of the three design variants was compared under defined static load cases to demonstrate the potential of hybrid casting.

As proposed in [24, 25], the use of a connection between the upper and middle front rails, such as a tension band, can improve the IIHS SOL performance. This tension band can be designed as a steel insert in an Al-cast shock tower using hybrid-casting technique which is the second objective of

![Fig. 5 Detailed images of a cast aluminium shock tower with external rib structure from a outside and b inside, as well as c example of a steel connecting plate which is joined to aluminium cast part by using rivets and adhesive bonding](image)
this work. To avoid any negative influence of the planned tension band and hybrid-casting technology in general on crash load cases with higher overlap, all shock tower variants were subjected to the FMVSS 208 Front Crash as well, as described in [26], with 100% overlap. The results were evaluated comparatively. Since the connecting plate for enabling spot welding of Al cast part to adjacent steel parts, as shown in Figs. 4c and 5c, is only a geometric design without significant performance impacts, it was not included in this work.

3 Concepts and design

3.1 Steel shock tower (V1)

The shock tower of the Honda Accord Sedan MY 2011 was selected as a reference. This vehicle is available in the National Highway Traffic Safety Administration (NHTSA) database as a complete vehicle finite element (FE) model for the LS-Dyna solver [27]. In this paper, the model is referred as “Accord_BL_V1.1y”.

All properties and boundary conditions, such as materials, joining techniques and contact conditions, were taken from the above-mentioned model after checking for plausibility. The model is designed with different mean mesh sizes depending on the vehicle area. The front-end structure, including the shock tower and its periphery, which is

Fig. 6 FE model of Honda Accord [27] and closer view of the front left shock tower with upper and middle front rail

Fig. 7 Detailed view of the reference steel shock tower of the Honda Accord with numbered components (defined in Table 1)
particularly relevant to this work, has a mean mesh size of 7–10 mm. The overall vehicle model and a detailed image of the relevant area of the shock tower (here: left side of the vehicle) are shown in Fig. 6.

This shock tower consists essentially of four components, the shock tower and three reinforcing elements, and is connected to the shock tower on the other side of the vehicle via a strut brace. The individual components are given in Fig. 7 and their thicknesses, as drawn from the database, in Table 1. The steel variant is called “V1” throughout the rest of this work.

### 3.2 Al-cast concept (V2-Al)

As a first comparison variant, an Al-cast shock tower concept was proposed in the periphery of the above-mentioned vehicle. Using reverse engineering based on the discretized FE model of the reference vehicle, the front-end structure of this vehicle was generated as a design file for CAD. The cast Al shock tower was modelled as a surface model in this environment. The main connection surfaces on the middle and upper front rails, the mounting position for the spring/damper and, as far as possible, the installation space for spring and damper in V1 (steel reference) were unchanged. General design principles for cast aluminium components were used. This pure Al-cast concept is referred as V2 (Fig. 8). Based on the study’s benchmark information, the shock tower was designed with a 3-mm-thick base body with a 6-mm-thick shock tower top. The V2-Al concept is

| No | Component   | Material     | Thickness [mm] |
|----|-------------|--------------|----------------|
| 1  | Shock tower | IF 260–410   | 2.0            |
| 2  | Reinforcement_1 | IF 260–410 | 1.8            |
| 3  | Reinforcement_2 | IF 260–410  | 3.0            |
| 4  | Reinforcement_3 | IF 260–410  | 1.8            |

Fig. 8 Basic shape of the shock tower casting concept in the periphery of the vehicle model

Fig. 9 a Dimensions of the shock tower V3-St-Al using steel to reinforce Al-cast part and the detailed dimensions of the steel inserts and b shock tower V1 and steel periphery parts which were integrated in V2-Al and V3 St-Al
shown in Fig. 8. In this stage, it is only a surface and place holder. The rib structures and further design details must be further developed in Chapters 4.2.3 and 5.1 using topology optimizations.

3.3 St-Al hybrid-cast concept (V3 St-Al)

The second comparison variant, and the primary object of investigation in this work, is a St-Al hybrid-casting design for the shock tower. This concept uses the basic geometry of V2-Al, which is reinforced at exposed locations by steel inserts, as shown in Fig. 9. Because the upper area of the shock tower with the spring supporting plate, where the damper bearing is also connected, represents the highest loaded areas of the shock tower (besides of crash load cases), it must be designed for the highest stiffness and strength. This area was thus selected for reinforcement with steel in the Al cast part to save package space.

The steel reinforcement in this area was designed as a "cup" with a small flange to avoid stress concentrations at the edge of the shock tower top and to ensure the manufacturability (limited formability) of the reinforcement made from ultra-high-strength steel.

In addition, a steel tension band was placed through the shock tower to connect the upper and middle front rails, also using ultra-high-strength steel, as shown in Fig. 2b). It should be noted that the connection point on the upper front rail was closer to the vehicle centre in the vehicle’s x-direction than the connection point on the middle front rail (see Fig. 2). Otherwise, it would not be possible to transmit forces properly between the two front rails in case of IIHS SOL crash loads.

The dimensions of this V3 St-Al variant (the outer dimensions of which also apply to the V2 Al variant) are shown in Fig. 9a). V3 has the same 3-mm-thick base body as V2 but is reinforced with 3-mm steel (DP800) in the top area, where the total wall thickness is also 6 mm (3 mm cast Al + 3 mm steel) as in V2. The area of the tension band is also 6 mm thick in total that consists of 3-mm cast Al and 3-mm steel (DP800). As for V2, the rib structures and further design details must be further developed in Chapters 4.2.3 and 5.1. Since Al cast may integrate several sheet metal stamping parts, several original steel parts shown in Fig. 9b were integrated in Al cast in both V2 and V3 variant.

4 Method

4.1 Derivation of the requirements

Before comparing the concepts presented in Chapter 3 and further developed the two new variants V2 and V3, both quasi-static and dynamic requirements must be defined. According to the requirements of several European OEMs which were generalized here, for a mid-size vehicle with an average axle load of 1000 kg, a maximum vertical force of approx. 60 kN may occur on the shock tower during misuse bounce tests. The longitudinal forces and the transversal forces are supported by the suspension link arms and bushings which are further supported by the sub-frames or body structures. At double wishbone suspensions (in case of Honda Accord here), there are only forces in-line with the damper which are mainly vertical. At McPherson suspensions, only minor longitudinal and transversal forces are transmitted to the shock tower. They are thus not further included in this development. From the total forces of 60 KN in vertical direction, 50 kN should be assigned to the damper and 10 kN to the spring (see Fig. 10). Since plastic deformation must not occur and it is difficult to define the begin of plastic deformation in FE models, a max. plastic deformation of 1–2 mm is defined as the target value.

As the shock tower is located in the crash-relevant area of the front body structure, the influence of the hybrid-casting technology on crash behaviour was investigated in addition to the influence for dynamic load cases. As defined in the objective of the present work, the crash behaviour in the IIHS SOL in particular must be improved by design modifications.

In this work, the vehicle \( m = 1685.55 \text{ kg} \) collided according to IIHS SOL test [21] at 40 mph (64.4 km/h) with a rigid barrier that had a 25% overlap with the vehicle front. In addition, the FMVSS 208 front crash [26] was investigated. The speed in the FMVSS 208 was 35 mph (56.4 km/h), and the vehicle mass was identical to the IIHS SOL.
4.2 FE models

As mentioned in Chapter 3, an FE model of the Honda Accord from the NHTSA database [27] for the LS-Dyna solver was used as the basis for the FE models in this work. The exact models for quasi-static and dynamic simulation, as well as for topology optimization, are presented in the following sections.

4.2.1 FE models for quasi-static simulations

The discretized vehicle model from [27] was exported and prepared for use with the Abaqus solver. To be able to calculate the elastic and plastic deformation of the shock tower including its reinforcing elements at a component level, simplified boundary conditions were defined. The principle is illustrated in Fig. 10.

It was assumed that the shock tower was ideally rigidly connected to its periphery without a degree of freedom. This assumption was implemented in the FE model by fixing the nodes at the edge of the shock towers, and in the case of V1, at the strut brace (all degrees of freedom = 0). Any elastic or plastic deformations from the periphery were thus not taken into account. This is advantageous for the comparison of variants V1–V3 planned here because it avoids the discontinuous boundary conditions that can occur when using different peripheries and connection points.

The load introduction for the quasi-static equivalent tests was implemented according to OEM specifications. As derived in Chapter 4.1, the spring and damper forces were considered in a differentiated manner. The spring force was introduced via an outer circular ring, corresponding to the spring diameter, using RBE2 elements to connect all finite elements of this circular ring as a "rigid-spider". The elements inside this circular ring were also connected with RBE2 elements to introduce the damper force there (see Fig. 10).

For V1, the positions of the individual components and their connection types were taken from the given LS-Dyna model and adapted for the solver of Abaqus. Bolted connections were realized with COUP_KIN and spot-welded connections realized with COUP_DIS elements. The connection between the steel inserts and the Al casting for the V3-St-Al shock tower was implemented as a node-to-node connection. As no other components were used in these variants due to the functional integration, no other connection techniques were necessary.

The quasi-static simulations were performed with elastic–plastic, isotropic and temperature-independent material models. The Young’s modulus for steel was considered in the calculations with 210 GPa, and stress–strain curves corresponding to the steels used (IF260-410 and DP800) deposited in the FE material card were used. The cast Al alloy A356 without heat treatment was assumed to have a Young’s modulus of 75 GPa, and a corresponding flow curve was selected.

To evaluate both elastic and permanent plastic deformation, a two-step simulation was performed. In the first time step, the shock towers were loaded with \( F = 50 + 10 \) kN and the load was held. The total deformation, including elastic and plastic deformation, was measured. In the second time step, the shock towers were unloaded (\( F = 0 \) kN) to determine the permanent plastic deformation.

The average mesh size for V1 was about 8 mm. The V2-Al and V3-St-Al variants were meshed and calculated with an average element size of 2 mm due to the upstream topology optimization, which resulted in a filigree rib structure.

4.2.2 FE model for dynamic simulation

For the explicit dynamic simulations with the LS-Dyna solver, the vehicle model from [27] was determined after a plausibility check to be applicable without any changes for reference V1 (see also Fig. 6). The barriers for the two crash load cases to be tested, IIHS Small Overlap [21] and FMVSS 208 [26], were already included in the FE model.

The V2-Al and V3-St-Al concepts were integrated into the existing periphery of the FE model accordingly to the reference and meshed with an average mesh size of 5 mm to ensure efficient calculations for the dynamic simulation. The directly adjacent sheet metal components of the reference were integrated into the V2-Al and V3-St-Al concepts (see Fig. 9). The V2-Al and V3-St-Al shock towers were connected at the upper and middle front rails over the entire flange length using rigid-body elements for simplification. To compensate for the stiffness of these elements, which is higher than that of the modelled spot welds used in reference V1 at a spacing of approximately 4 mm, the spacing between the rigid-body elements was increased. In all concepts, the strut brace was connected to the shock towers by means of rigid-body elements that simulated a bolted connection.

Four section forces measured on representative cross sections in the periphery of the shock towers (MB, MF, UB and UF) were used as the basis for comparisons and success checks of the different shock tower variants and their influence on the load paths under crash loading, as shown in Fig. 11.

4.2.3 Topology optimization of variants V2-Al and V3-St-Al

To take advantage of the design freedom offered by the Al casting in V2-Al and V3-St-Al, a topology optimization with the goal to increase the stiffness was carried out for both variants using the Optistruct solver. Based on the 3 mm
thick Al-cast basic geometry, which was pre-designed in the periphery of the vehicle model and corresponds to the current state of the art (see Fig. 8), design spaces for topology optimization were defined (see Fig. 12).

The areas of the defined design spaces were non-critical regarding the package space on the basis of the FE vehicle model. The areas of the shock towers in the positive and negative vehicle \(x\)-direction (side) and the vehicle \(z\)-direction (outside of the spring/damper mounting area) were approved for topology optimization with a distance of up to 20 mm, as shown in Fig. 12. The dimension of 20 mm corresponds to the average maximum rib height in this area required by the cast shock towers in the benchmark.

As is common for Al-cast shock towers, and package space above the shock tower top was also made available for topology optimization. In this region, a maximum rib height of 5 mm was defined due to the limited package space for the installation length of spring and damper. This results in a minimally increased design space requirement for the variant V2-Al compared with the reference variant V1. This did not result in a direct package space violation due to intrusion into existing components of the vehicle.

As the vehicle \(y\)-direction of the shock tower was directly connected to the periphery, including the engine and auxiliary aggregates, no package space was released there. The package space was meshed with Tetra elements with an average mesh size of 2 mm.

Using the basic geometries of V2-Al and V3-St-Al, the defined design spaces and the boundary conditions with regard to fixation and force application from Chapter 4.2.1, topology optimizations were carried out for both variants with the following parameters: optimization target: minimum compliance; constraint: volfac = 0.2, reduce static displacement; and mindim = 1.0 mm, maxdim = 3.0 mm, mingap = 15 mm and draw \(z = -1\). These constraints were based on the state of the art regarding rib designs in the area of a shock tower. The optimization of objective minimum compliance meant, in turn, maximum stiffness. The results of the topology optimization and the rib structure itself thus primarily served to increase stiffness for the quasi-static equivalent load cases (whose boundary conditions also served as the basis for the topology optimization) and not for the dynamic crash load cases.

5 Results and analysis

5.1 Topology optimization

The calculations for topology optimization based on the boundary conditions named in chapters 4.2.1 and 4.2.3 using Optistruct allowed for the comparison of the shock tower deformation with and without a calculated reinforcement structure (in the form of ribs). As the topology optimization ran in the linear elastic region only, the results presented in Fig. 13 demonstrate the resulting elastic deformation of the shock towers V2-Al and V3-St-Al.

The upper half of Fig. 13 shows V2-Al has a displacement of 7.21 mm, which is 0.983 mm higher than V3-St-Al at 6.227 mm. These results were generated before
the optimization (i.e. without rib structure). After optimization, the displacements of both variants were significantly reduced to 1.943 mm (V2) and 1.82 mm (V3-St-Al), as seen in the lower half of Fig. 13.

In addition to the elastic deformation, the ideal material distribution in the given design space under the defined boundary conditions could be obtained based on the topology optimization calculations (see Fig. 14). The results for V2-Al and V3-St-Al differed only slightly in the last iteration (i.e. after convergence had been achieved). This minimal difference can be explained by the different stiffness of the two versions due to the steel inserts in V3-St-Al. Because only the potential of the hybrid-casting technology is to be investigated, and because differences in rib structure between V2-Al and V3-St-Al would represent an additional variance, the topology optimization result of V2-Al was converted into a rib structure and applied to both versions. The corresponding results of the topology optimization and their interpretation for V2-Al are shown in Fig. 14.
V3-St-Al shows higher stiffness due to the steel inserts. This advantage was used to increase the package space for the spring/damper package. The ribs with 5 mm height at the shock tower top were removed consequently, and the freed-up space was used to move the attachment surface for the strut mount by 5 mm in the positive \( z \)-direction. Conversely, this meant an increase of 5 mm in the installation space for the spring/damper assembly, as shown in Fig. 15. With this exception, the rib design for V3-St-Al was adopted from V2-Al.

After constructive implementation of the rib structure based on the topology results, the elastic deformation of the V2-Al and V3-St-Al variants was calculated with the Abaqus solver to verify the topology results. As an example, the results of variant V2-Al are shown in Fig. 16. An elastic displacement of 1.874 mm (calculated with Abaqus; for boundary conditions, see Chapter 4.2.1) was achieved by building the ribbed structure. A comparison with the result of the topology optimization in the last iteration, which shows a deformation of 1.943 mm, shows a very good correlation.

For V3-St-Al, the topology results and the calculation (solver: Abaqus) with the interpreted rib structure were also almost identical to the last iteration.

### 5.2 Quasi-static calculations

The above optimization and verification were done based only on elastic deformations due to the restrictions of OptiStruct. As both elastic and plastic deformations must be considered, the following quasi-static calculations using the model in Fig. 10, which include plasticity, were conducted and compared. Since the weight of the shock towers plays a decisive role in the design decision, a weight comparison of the different concepts is given in Table 2. It shows that V1 was the heaviest variant at 4.12 kg, as expected, followed

| Variant | Plastic displacement [mm] | Weight [kg] | Specific stiffness [kN/mm*kg] |
|---------|---------------------------|-------------|-----------------------------|
| V1      | 1.655–3.035               | 4.12        | 8.8–4.8                     |
| V2-Al   | 2.568                     | 3.15        | 7.42                        |
| V3-St-Al| 1.135                     | 3.54        | 14.93                       |
by the hybrid-cast variant V3-St-Al at 3.54 kg, and V2-Al at 3.15 kg.

**V1**

The quasi-static calculation of V1 using Abaqus, the material data in Table 1 and the boundary conditions in Fig. 10, showed a comparatively high plastic deformation of 3.035 mm, higher than the required plastic deformation of less than 2 mm.

To obtain valid comparable values for V1, the material DP800, which is analogous to known material applications at OEMs, was therefore used in further calculations to model first reinforcement_3 and then reinforcement_1 of V1.

This material exhibits significantly increased strength compared with the original material IF260-410. Plastic deformation could be reduced to 1.655 mm using DP800 for reinforcement_3 and reinforcement_1. However, the effect when modelling reinforcement_3 with DP800 is very small, as the force transfer is realized by RBE2 elements in this component, and RBE2 elements have a stiffening effect on the component. The effect of the higher strength material is thus almost completely lost for reinforcement_3.

**V2**

The version V2-Al, shown in Fig. 14, was calculated implicitly with the same boundary conditions as the reference (cf. Figure 10). The results for elastic and plastic deformation are shown in Fig. 17a) and those for the remaining plastic deformation in Fig. 17b). The total deformation was 4.442 mm. The remaining plastic deformation was 2.568 mm, which is higher than the target value of < 2 mm defined in Chapter 4.1.

**V3**

Like V2-Al, the version V3-St-Al was calculated implicitly with the same boundary conditions applied for V1 and V2-Al, and the results are shown in Fig. 18. The remaining plastic deformation of 1.135 mm is clearly below the target value of 2 mm. Compared to V1 and especially V2-Al, an enormous increase in stiffness (reduction of plastic deformation by approximately 56% to V2-Al) can be observed. Taking into account the 5 mm increase in installation space in the z-direction and a 14% weight reduction compared with V2-Al, V3-St-Al demonstrates the high potential of hybrid-casting technology for stiffness-relevant components such as the shock tower.

Based on the quasi-static comparisons, it can be concluded that reference V1 had the highest weight and the lowest stiffness. With almost complete use of the existing package space, the cast Al variant V2-Al — depending on the basis of comparison — had slightly higher stiffness with a weight saving of approximately 24% comparing to steel reference V1. However, it failed to meet the plastic deformation target. The hybrid-cast shock tower V3-St-Al provided 5 mm more package space for the spring and damper with a weight saving of approximately 14% comparing to steel reference. It had significantly higher stiffness.
To compare the mass and stiffness of the different concepts, a specific stiffness factor was introduced which is the ratio between stiffness and weight of the part. V3-St-Al showed a value of 14.93 kN/mm*kg, which is twice as high as that of V2-Al at 7.42 kN/mm*kg. These values are added in Table 2 along with the plastic deformation and weight numbers.

5.3 Dynamic FE simulation

To investigate the influence of the different shock tower concepts in crash load cases, the IIHS SOL and the FMVSS 208 Front Crash were analysed using the FE models described in Chapter 4.2.2. As the V3-St-Al hybrid-casting concept was reinforced with a tension band for load path distribution, as shown in Figs. 2 and 9, the following evaluations focus on force distribution in the upper and middle front rails for the different load cases.

5.3.1 IIHS 25% with small overlap

For the IIHS SOL, the internal force–time curves at the four locations defined in Fig. 11 for the three concepts, as shown in Fig. 19. Very similar force curves and levels were found for V1 and V2-Al. As expected, the V2-Al concept did not have a significant positive or negative effect on the

Fig. 19 Plot of force–time curves for a V1, b V2-Al and c V3-St-Al for the IIHS SOL.

Fig. 20 Comparison of section forces of the shock tower a V1 vs. V2-Al and b V1 vs. V3-St-Al showing force transfer from upper to middle front rails
load distribution between the upper and middle front rails compared to V1.

In contrast, V3-St-Al exhibited a reduction in the force level in the upper front rail behind the shock tower by about 10 kN at the peak and a more homogeneous overall force level in the range of 20–90 ms (Fig. 19c). The force level in the middle front rail behind the shock tower of this variant is higher at 20–60 ms.

To show this load transfer effect more clearly, Fig. 20 compares the force curves behind the shock tower versions V1 vs. V2-Al and V1 vs. V3-St-Al. The first comparison (Fig. 20a) shows similar force curves for V1 and V2-Al. In each case, the force in the upper front rail was slightly reduced for V2-Al at 60–100 ms, which was due to the higher stiffness of the Al-cast shock tower than the steel reference.

When the hybrid-cast version V3-St-Al is compared with the steel reference V1 (Fig. 20b), there is a clear transfer of forces from the upper to the middle front rails in V3-St-Al. Due to the positioning of the tension band from the bottom-front to top-rear (z-x direction), the tension band showed a very early effect in the crash event: at approximately 20 ms, the upper front rail force increased compared to V1. After 50 ms, this force wave was strongly reduced, as targeted in the concept (Fig. 2). Because the forces in the middle front rail were also reduced, the tension band not only transferred force from the upper to the middle front rail, but also homogenized the force distribution.

5.3.2 FMVSS 208 front crash

As shown in Fig. 21, all three variants had similar section force curves and levels in the FMVSS 208 front crash at the cross sections used for the evaluation. The only significant difference can be observed in the section force behind the shock tower of the upper front rail in the hybrid-cast version V3-St-Al (Fig. 21c, UB). Due to the stiffer shock tower design, which was caused by the steel insert in the top area, the force level of the upper front rail behind the shock tower in V3-St-Al was about 10 kN lower than in

Fig. 21 Plot of force–time curves for a V1, b V2-Al and c V3-St-Al for the FMVSS 208

Fig. 22 Comparison of the accelerations of the vehicle centre for all shock tower versions in FMVSS 208
the other two variants between 40 and 80 ms. An overall force distribution caused by the tension band can also be observed.

The deceleration values in Fig. 22 show generally similar values in an uncritical range. The steel inserts in the shock tower and the tension band in the hybrid-cast design thus had no negative effect on frontal crash results.

To conclude the crash analysis, it can be stated that the tension band, which is ideally integrated into the St-Al hybrid-cast shock tower, has clearly shown its potential to contribute to a more balanced force distribution in the front body structure during the IIHS SOL test. The maximum force was reduced by approximately 27% and 8% on the upper and middle front rails, respectively. Furthermore, the tension band was able to transfer the load from the upper front rail, which was engaged in the SOL, to the middle front rail, as desired.

The investigations further show no indications that the use of hybrid-casting technology in the areas of the shock tower top and the tension band leads to negative effects in crash load cases with high (or complete) overlap.

### 6 Conclusions and outlook

In this work, quasi-static analysis was first performed on the original steel shock tower using a publicly available FE model of the Honda Accord MY2011 to subsequently develop and design a generic Al-cast and St-Al hybrid-cast shock tower, which were built as an FE model. For the purpose of building them, a basic design suitable for casting was designed in the periphery of the Honda Accord. Then, a load-optimized rib design for the Al-cast and St-Al hybrid variants was developed by topology optimization. The possibility of inserting a tension band for the IIHS SOL was also taken into account in the design of the hybrid-cast variant.

Quasi-static tests and dynamic crash tests were conducted on the three variants to assess the potential of hybrid-casting technology for use in the shock tower. The following results can be summarized based on the FE simulations.

First, it was shown that the use of hybrid-casting technology in the connection area of the front spring and damper can significantly increase the quasi-static and dynamic properties of the shock tower compared with a conventional steel design or an Al-cast design. In the proposed concept shown in this paper, which has further optimization potential, the following advantages were identified:

1. significant increase in stiffness (decrease in plastic deformation of up to 63%)
2. weight reduction of approximately 14%
3. gain in installation space in positive vehicle z-direction due to the elimination of ribs in the upper area of the shock tower by 5 mm

Points 1 and 2 are reflected in the specific stiffness values of the variants: the V3-St-Al hybrid-casting variant had the highest value of 14.93 kN/mm*kg, followed by V2-Al at 7.42 kN/mm*kg and the reference at 4.8–8.8 kN/mm*kg.

The effects of the different concepts on the force curves in the upper and middle front rails of the front body structure in IIHS SOL and FMVSS 208 front crash with 100% overlap were further investigated. The following key facts are worth highlighting:

1. significant differences in the force paths and, thus, the proposed concept’s influence on the load path distribution were found for the hybrid-cast concept in the IIHS SOL
2. a tension band in the form of a steel insert between the upper and middle front rails homogenized the force levels between these two decisive load path components
3. a slightly reduced force level was found at the front rails of the hybrid-cast concept in the FMVSS 208 front crash, which had no influence on body decelerations

This work has shown that the use of a tension band with hybrid-casting technology has positive effects on force distribution in the front-end structure during the SOL. However, to exploit the full potential of hybrid-casting and the tension band, adjustments to the periphery are necessary to fulfill the increased stiffness of the hybrid-cast shock tower. In particular, the lower A-pillar node and the A-pillar on which the upper front rail is supported should be mentioned here. Strengthening the firewall cross member could also be beneficial as required. Furthermore, the potential with regard to quasi-static stiffness and strength has not been fully exploited. It appears to be worthwhile to carry out a detailed design of a shock tower with regard to the special processes of hybrid-casting technology.

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**Declarations**

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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