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Redesigning and non-linear parametric and free-size optimization of an Mg alloy automotive seat frame

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ABSTRACT

The application of Mg alloy parts in the automotive industry is increasing to reduce weight and fuel consumption. One of the high potential parts for the application of Mg alloys in the front seat frame. However, change of material is accompanied by a change of the manufacturing process and change of design for the seat frame. In the present research, while keeping the reference overall ergonomic outline, a new substitute Mg alloy design was proposed, featuring a simple and easy to manufacture Z profile. Next, a two-stage optimization technique (size and shape) is proposed for the Mg seat frame based on the stress and displacement criteria of standard test plans. The final optimized design is close to a fully-stressed state and is 70% lighter than the reference steel backrest. The low density of Mg compensates the effect of thickness increase on seat frame weight and material cost.

1. Introduction

Throughout automotive industry history, manufacturers have moved towards lighter cars to decrease fuel costs and environmental pollution. To reduce weight, two main approaches are on the agenda; the first one is changing the design and optimizing the structure, and in the second approach, new lighter materials are introduced and new applications are being developed [1].

In recent years, the use of magnesium alloys with high specific strength has significantly increased. Due to their high anisotropy and poor formability, Mg alloy parts in the automotive industry are mainly manufactured by high pressure die casting [2]. Although Mg alloys have low ignition temperatures [3] and their casting requires specific measures [4], their die-casting features various benefits compared to Al alloys. Such benefits include (1) higher fluidity (lower die-cast pressure) [5], (2) lower specific heat (higher production speed) [6] (3) not forming intermetallics with steel dies (less die wear) [6], and (4) ability to cast thinner walls (saving material and casting even lighter parts) [6]. These features are important in designing lightweight and optimal parts for vehicles.

Considering the lower strength of Mg alloys compared to Al alloys [2], Mg parts in the automotive industry are traditionally designed and utilized in cases that require lower mechanical strength to protect other sensitive parts (such as gearbox housing) [7]. With the advent of modern technologies, new Mg alloy structural parts are introduced. For instance, the instrument panel [6] and shock tower [4] are made by die-casting and the trunk lid [8] is made by sheet forming. Lightweight Mg seat frames are also among new structural parts that have received notable attention in the automotive industry [6], [9].

Currently, steel seat frames are common in the industry. The frame consists of many individual

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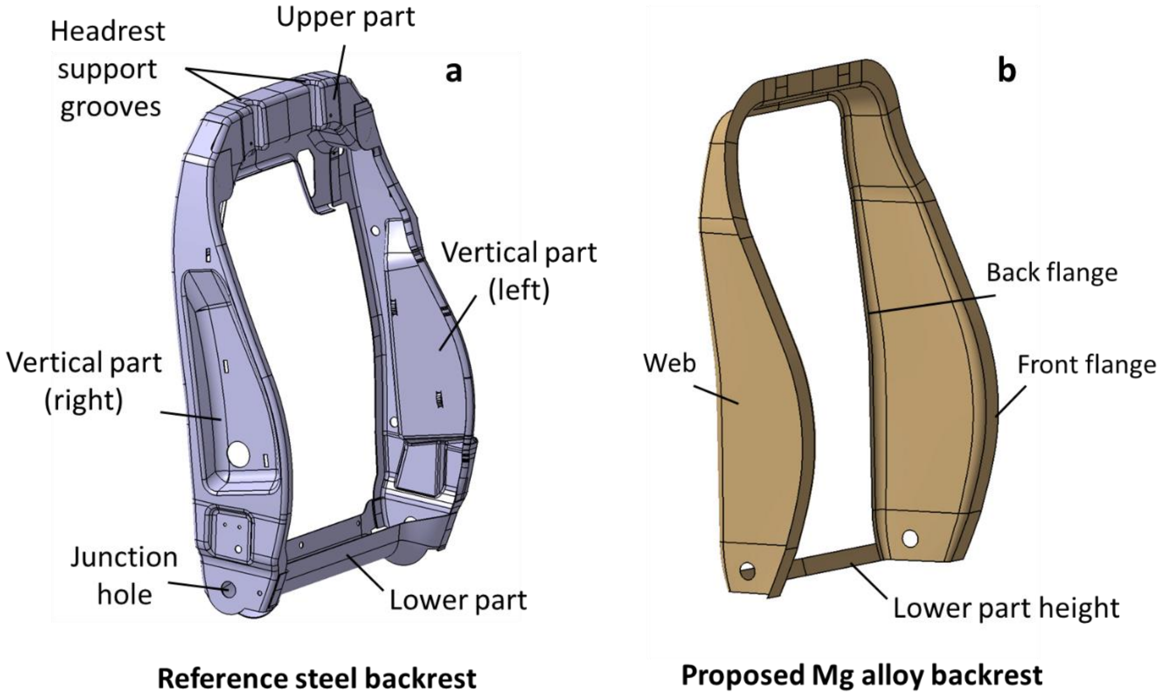

Figure 1: CAD drawing of the (a) reference steel backrest and (b) the proposed Mg alloy backrest

steel tubes, brackets, wires, and sheet-formed parts that are joined by welding. By die-casting a single Mg part, engineers have significantly reduced the seat frame weight [6]. The benefits of an Mg seat frame compared to conventional steel frames includes; (1) weight reduction by utilizing a low-density alloy and optimizing geometries including thickness. (2) Simple assembly and faster production by less welding and machining, and fewer manufacturing steps. (3) Noise reduction by decreasing the number of components and connections, and benefiting from the damping properties of Mg.

For instance, Mercedes has used Mg die-castings in the integrated seat structure with a three-point safety belt in the SL Roadster [10]. It's newly designed Mg alloy complete seat structure weighs only 8.5 kg with a varying wall thickness of 2–20 mm [10]. Noteworthy, Hyundai-Kia Motors Corporation (HKMC) has introduced seat frames made by bending and joining Mg extruded profiles [11]. The new frames have reduced 6 kg per car [12]. Utilizing the Mg seat frame HKMC's Mg consumption has raised from 670 to 3700 tons per year in a 3-year period [10].

Other than aesthetic features, the car backrest should withstand extreme loads and undergo controlled damage during a vehicle crash. ECE-R17 regulations provide the criteria for a safe vehicle seat frame design [13]. Different researchers have studied Mg seat frame designs To design a front seat backrest according to ECE R17, researchers have employed FEM and topology and free-size optimization [14]. In another research, 5052 Al-alloy is replaced by ZK60A and AZ31B in a seat frame and 33% weight saving is reported [15]. In [16] the possibility of using Mg is investigated and the results are compared with carbon steel which shows superior overall properties. The results of other studies indicate that although Mg is more expensive than steel, the weight saving and manufacturing process can compensate for costs [17].

In all the previous studies, an initial seat design is optimized to reduced weight. However, in the present study, a steel backrest is redesigned, keeping its outer geometries to be diecast by an AM60 magnesium alloy. For this purpose, the overall geometry and curvatures of the original seat are preserved while changing the main structure into a swept Z profile with variable dimensions along the outline of the seat. A finite element analyzer-(size) optimizer procedure is applied to the proposed model in order to get the best values for the profile dimensions while meeting the required load-displacement standards. Next, another finite element analyzer-(shape) optimizer is applied to the resulted model in order to find the best thickness distribution for the structure. The results show that the new design is significantly lighter than the original steel backrest (~70%), yet enough strong to qualify all the standard criteria.

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Table 1: Mechanical properties of steel and magnesium alloys used in the reference and new backrest

Alloy	Density (g/cm^3)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Poisson's ratio	Young's modulus (GPa)	Final elongation
ST12 steel	7.85	210	270-350	0.3	210	38%
AM60 Mg alloy	1.77	124	228	0.35	45	15%

2. Modeling procedure

2.1. Description of the steel reference backrest

In Fig.1a, a CAD drawing of the reference steel backrest (as obtained from the manufacturer) is shown. It consists of two vertical parts (left and right) and two horizontal parts (upper and lower). These four pieces are formed by stamping and bending and then joined by spot and partial seam welds to each other and to other smaller parts such as nuts, bolts, rods, and brackets. The headrest support is welded to the backrest by two tubes placed in the grooves of the upper part.

As shown in Fig.1a, the backrest is connected to the base through the junction hole. The steel used in modeling this design has the mechanical properties presented in Table 1. As shown in Table1, Mg presents lower mechanical properties both in modulus and strength. The total weight of the reference steel backrest is 2.96 kg.

2.2. The Magnesium alloy backrest

The proposed Mg alloy backrest is designed to have the same outline as that of the reference backrest. Die-casting requirements limit the new design profile to shapes that can be easily extracted from the high-pressure casting die. The main casting limitations are in angles, profile shapes, and directions, hollow sections, and thickness. For instance, a U-shape profile with flanges parallel to the backrest plane may not be extracted from the die after solidification. Therefore, special constraints are considered in the part design to make it suitable for a single step high-pressure die to cast without cores and minimum final machining. Seeing the diecast limitations, a Z profile sweeping along the reference backrest outline is selected for the new design (see Fig. 1b).

As shown in Fig.1b, the profile consists of a web and two flanges in the back and in the front. The material selected for this design is AM60 Mg. The proposed alloying composition is suitable for die casting (high fluidity) and presents sufficient strength (see table 1) and formability as it is strengthened by both solid solution and precipitation [14], [18].

2.3. Load conditions

Different tests are designed to represent the forces applied to a seat in a crash from the front, rear and sides of the seat. Two of the most important tests described in the European standards (UNECE R-17) are considered as references in this study. These tests consist of (1) the backrest moment test, and (2) static strength of headrest. The aim and conditions of each of these tests are

Table 2: Aims and conditions of backrest tests according to UNECE R-17

#	Test Name	Aim	Conditions
1	Backrest moment	Measuring the strength of the backrest and other components attached to the backrest	A bending moment of 530 N-m in the H-point should be applied on the backrest frame*.
2	Static strength of headrest	Measuring the resistance of the backrest and the headrest to the loads involved	Initially, a 373 N-m bending moment in the H-Point should be placed on the backrest. Then an additional moment of 373 N-m about the H-point should be applied at a distance of 65 mm below the topmost point of the headrest, with a D=165 mm sphere. The force applied to the backrest is further increased to 890 N*.

*Acceptance criteria: No fracture should occur on the backrest.

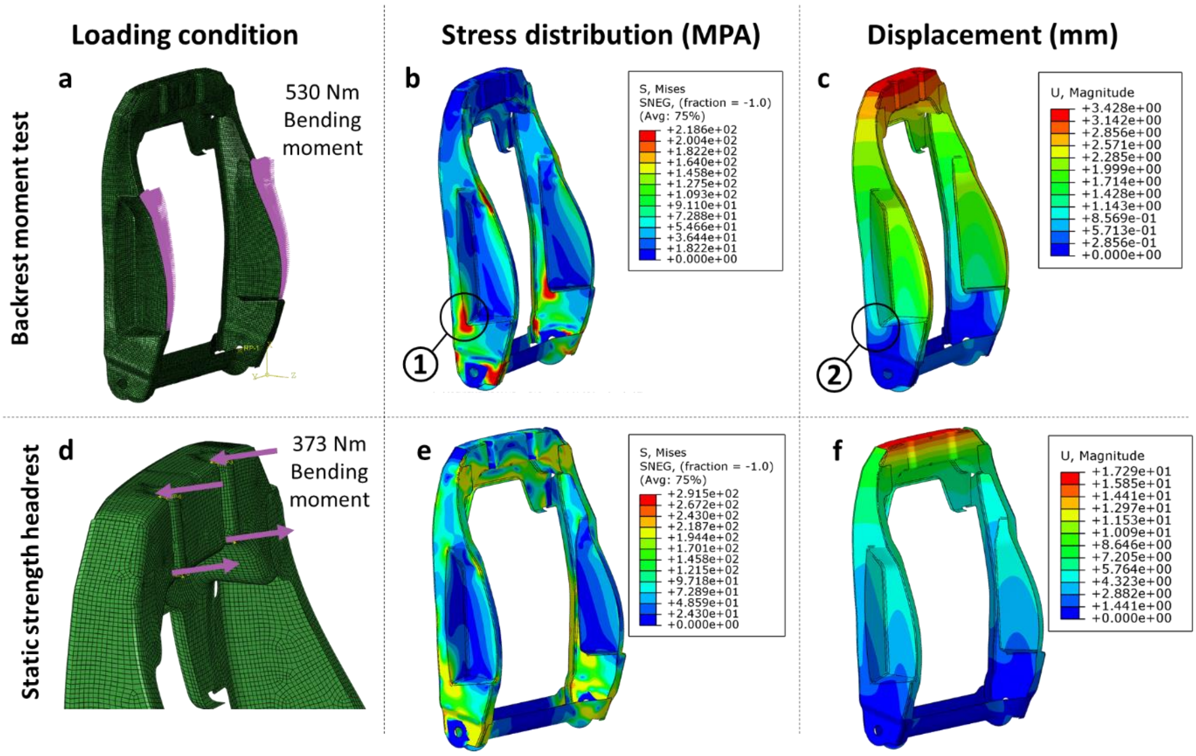

Figure 2: Loading conditions, stress and displacement distribution on the steel reference backrest

summarized in table 2 with descriptions. In all the mentioned tests the seat frame is loaded in real-time quasi-static conditions, and thus neglecting the inertial loads

It should be noted that other than the mentioned backrest test in table 2, which tests the strength against bending momentum, there is another test that is designed to examine the proper functioning of the seatbelt mechanism (the seat anchorage test). This testing condition is not considered in the present study. To completely examine the functionality and safety of a backrest, more standards are developed which are focused on

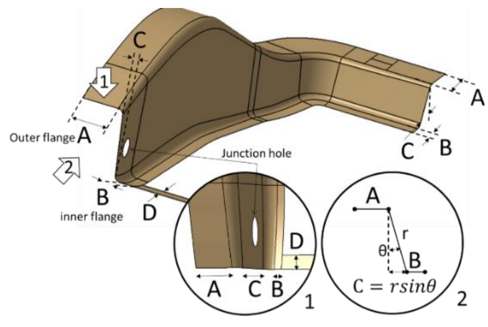

Figure 3: Geometrical optimization variables in the proposed Mg backrest

dynamic loads. In the present paper, the static loading conditions are considered solely.

2.4. Simulation

In order to gain an idea of how the reference backrest responds to the above-mentioned tests, its mechanical behavior is investigated using the finite element method, considering an elastic-plastic material behavior. Thin sheets are approximated as 3D surfaces in the CAD model. A specific meshing module is used for accurate meshing. The other important boundary condition is located at the attachment connecting the backrest to the base frame. The two parts are connected by bolts, nuts and other auxiliary parts. Therefore, the load-bearing contact surface is larger than the junction hole diameter. For modeling the screw, an intermediate point in the center of the junction hole is selected and coupled to the elements around the hole with 6 degrees of freedom. It is assumed that the screw does not rotate in its main axis.

To apply the 530 Nm bending moment at the H-Point (test no. 1), distributed triangular loads are applied on vertical parts of the backrest (Fig.2a). Based on the test plans, on the upper portion of the backrest, a force producing a 373 N-m moment about the H-point should be applied rearwards to the frame. a confidence coefficient of 10% is considered for all the forces in all simulations of this study. For instance, instead of 530 Nm, 583 Nm bending moment in the H-Point is applied on the backrest for the backrest moment test.

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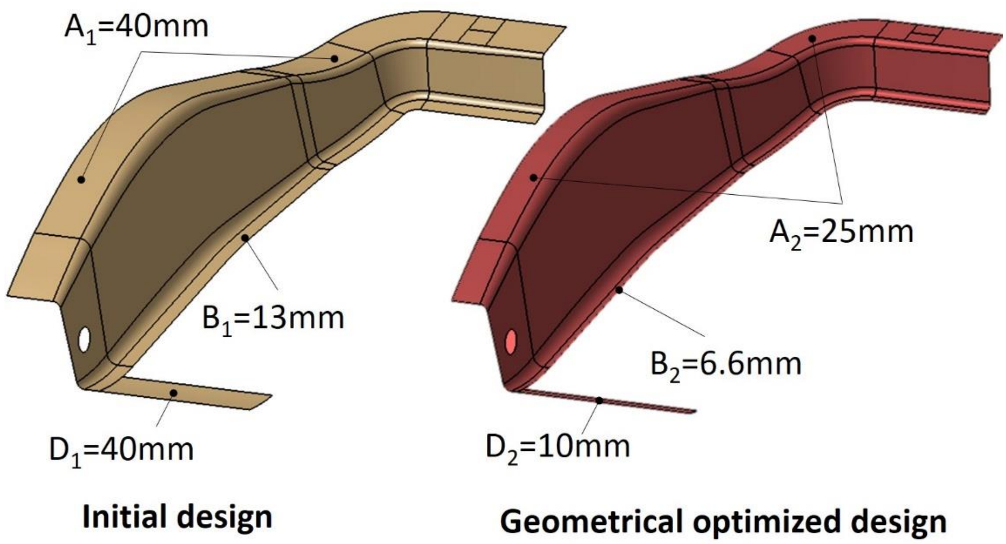

Figure 4: The initial and the geometrically optimized designs of the Mg alloy backrest

The von-Mises stress distribution in this backrest after applying the moment is shown in Fig.2b. As could be seen in the figure, the maximum stress is 218 MPa, which occurs at corners of the lower portion of the vertical segments. This is expected because of higher internal moments and stress concentration. Next are the regions surrounding the junction hole that connect the backrest to the base frame, which is attributed to high internal moments. Fig. 2c shows the overall displacement distribution in the backrest for this test. As shown in the figure, a maximum displacement of 3.42 mm occurs at the upper part, which is below the acceptable standard-stated value of 21 mm [14].

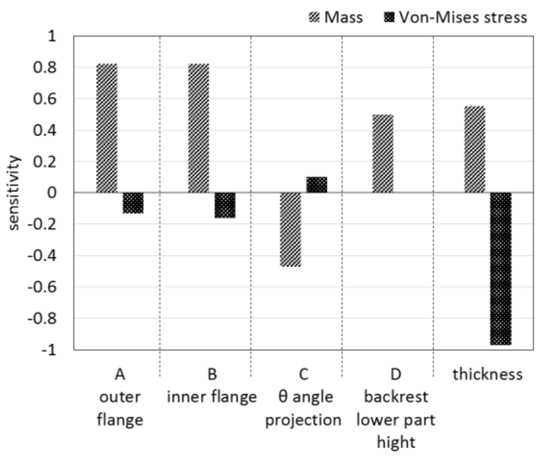

Figure 5: Sensitivity of different geometrical dimensions on the backrest mass and the maximum stress

As for the static strength of the headrest test (test no. 2), other than the 373 Nm bending moment on the headrest, a 165 mm diameter sphere should apply a force producing a 373 N-m moment 65 mm below the maximum point of the headrest (Fig.2d).

The von-Mises stress and overall displacement distributions are shown in Fig. 2e and 2f, respectively. As shown in Fig.2, at the stress concentrating regions, the stress reaches higher values than the AM60 yield stress (point 1 in

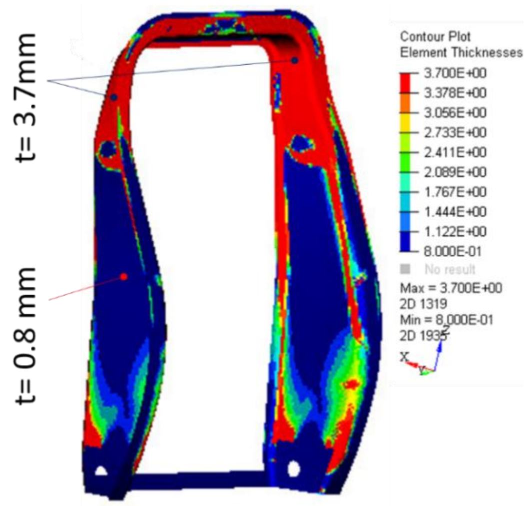

Figure 6: Thickness distribution of the Mg alloy backrest after shape optimization stage.

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Table 3: Optimization parameters and dimensions before and after optimization

Dimension (mm)	A outer flange	B inner flange	C web projection	D backrest lower part height	uniform thickness
Primary Mg backrest geometry	40	13	17	40	5
After geometrical optimization	25	6.6	17	10	3.7

Fig.2b). However, by comparing the displacement contours it can be seen that the displacement in the same regions is very low and incomparable to the plastic strain threshold (point 2 in Fig.2b). Consequently, these regions do not pose any threats to the overall seat safety [19].

3. Multi-stage optimization of the proposed Mg frame

Now that the finite element analysis of the backrest is established, it can be used to implement the optimization phase of the design, using the optimizer module of the finite element software. The objective is the weight of the backrest, while the strength and displacement criteria are considered as constraints. It should be noted that due to symmetry, only half of the backrest is modeled. This optimization takes place in the following two phases.

3.1. Sizing (geometrical) optimization

As previously stated, the geometry of the magnesium backrest is a Z-profile, swept along the same outline of the reference backrest, but having different web size along the outline. The transition between sections is a smooth swept surface. The design variables at this stage of the optimization include (see Fig. 3) (1) A, the length of outer flange, (2) B, the length of inner flange (3) C, the projection of the web length on the backrest plane, (4) D, the height of the backrest lower part, and (5) the uniform thickness of the profile. It should be noted that in order to maintain the backrest ergonomic shape, the web size of the Z profile (dimension r in Fig. 3) is kept fixed in the optimization process but its angles from the backrest planes (the inner flange) are considered as a design variable. As previously discussed, all the variables may change only in ranges that leave the geometry suitable for die-casting. For instance, the

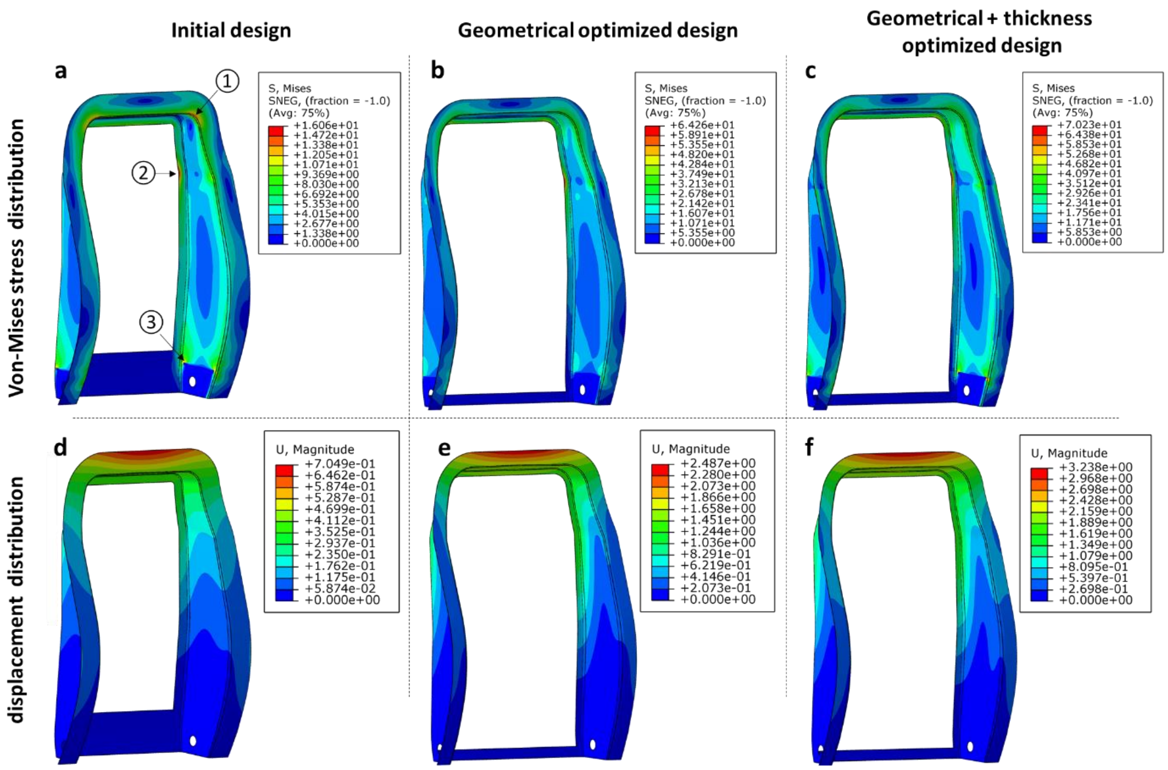

Figure 7: Simulation results of the Mg alloy seat frame in the backrest moment test (a-c) von-Mises stress and (d-f) displacement distribution.

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θ angle should not become negative since retracting the solidified part from the die would become impossible. Geometrical optimization is performed by the ISIGHT software.

3.2. Shape optimization

Once the optimum size of the Z profile is obtained, the second optimizer module is capable of changing the thickness of shell elements locally. By the shape optimizer, weight is reduced, constraints are satisfied and an almost fully stressed design is approached. Important to note that the thickness non-uniformity will not pose any problem in the manufacturing process. However, a lower thickness limit of 0.8 mm is considered due to limitations in filling thinner walls in die-casting. The shape optimization was performed by the OPTISTRUCT software.

4. Results

4.1. Nonlinear parametric optimization

Simulations on the steel backrest and previous reports [19] indicate that the stress concentration in the static strength headrest test (test 2 in table 2) is significantly larger compared to the backrest strength test (test 1 in table 2). Therefore, to obtain the optimally sized model, only the simulation results of this test were considered. A built-in evolutionary optimizer with 1000 iterations was used to achieve the overall optimal condition. Table 3 shows the initial dimensions which are selected based on the primary Mg backrest geometry (Fig.1b) and the results of the first stage of the optimization (sizing). Results indicate that after shape optimization, the primary thickness of 5mm is reduced to 3.7mm by geometrical optimization. In the next step the thickness is optimized across the frame and in some regions, the proposed optimized design, walls are thinner than the reference steel backrest. Noteworthy, the initial thickness of the steel backrest was 1.25mm.

In Fig.4 the CAD drawing of the Mg backrest before and after geometrical optimization is shown. It can be seen that the size of both the inner and outer flanges are reduced in the optimized design.

It is interesting to note that although as a design variable, the angle between the web and flanges was free to change, it remained at its initially set value. This can be justified using a sensitivity analysis, which will be presented later.

4.2. Sensitivity analysis in parametric optimization

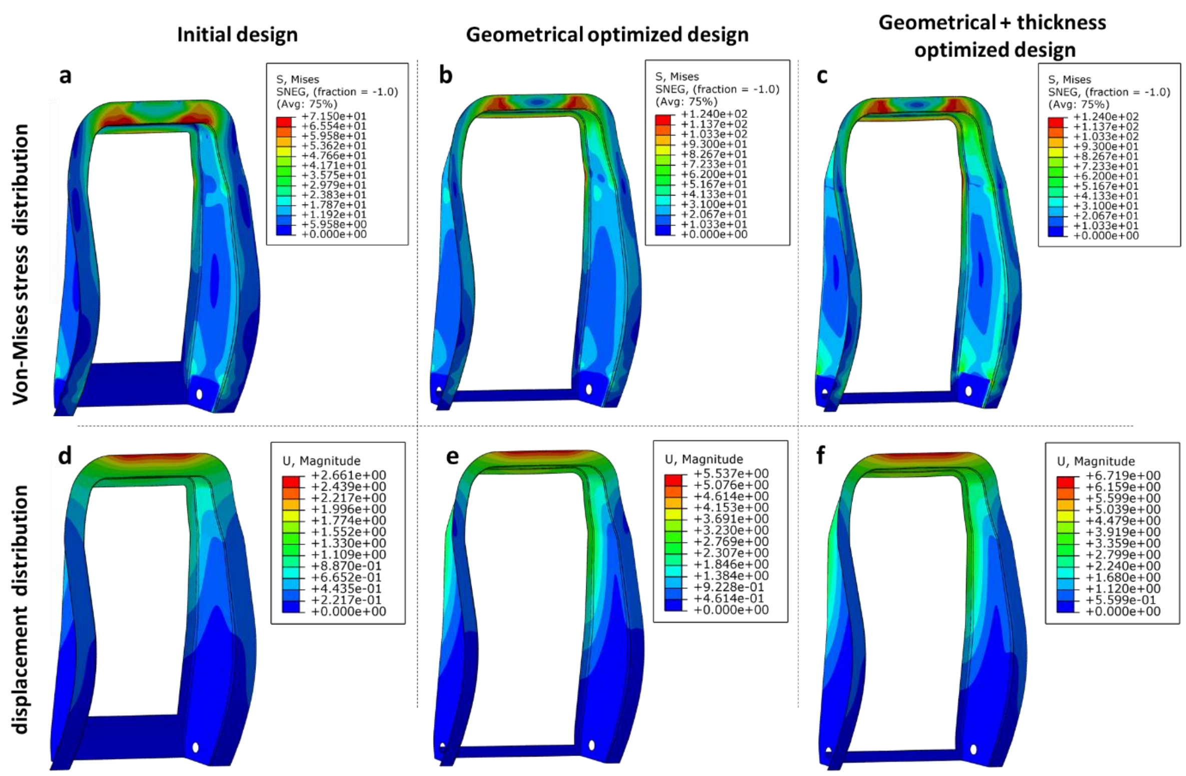

Figure 8: Simulation results of the Mg alloy seat frame in the static strength headrest test (a-c) von-Mises stress and (d-f) displacement distribution

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Dependency and sensitivity analysis of physical properties on different design variables can be used to speed up the design process and to better understand the system's performance [20]. In Fig.5 sensitivity analysis of the geometrical parameters (table 3) on backrest mass and maximum Von-Mises stress are presented. sensitivity is calculated by the optimization code while changing the parameters to reach the optimum condition. In Fig.5 the positive and negative values indicate that the variable has a positive or negative effect on the physical parameter. For instance, if the thickness increases, the weight of the seat backrest is also increased (similar direction). However, by reducing the thickness, maximum Von-Mises stress increases (opposite direction).

The data of Fig.5 indicates that by increasing all the variables except the web projection (C), the mass is increased. Nevertheless, increasing web

4.3. Shape optimization of the shell model

As mentioned in the previous section, the shape optimizer module of the finite element software allows an overall optimized design to become more optimum by changing the local thickness of the shell parts, which were considered to be uniform in the first stage of optimization. Fig.6 shows the thickness distribution after the shape optimization process. For this stage, the minimum allowed thickness for the Mg part was taken to be a practical value of 0.8 mm [14]. Moreover, sudden thickness changes were modified manually in order to eliminate stress concentration locations [11]. The figure shows that a considerable portion of the backrest is at its minimum thickness which contributes to a lower weight compared to that of the first stage of optimization. Noteworthy, casting parts with variable thickness is possible with high pressure die-casting [4] and similar approach has employed by other researchers to optimize mechanical properties [21] and crashworthiness of automotive [22].

projection increases maximum stress. The data also shows that the inner and outer flange dimensions have the highest impact on the backrest mass while thickness has the highest impact on maximum stress.

geometrical dimensions of the Z profile and uniform thickness, a sizing optimization was performed on the Mg backrest, followed by a shape optimization that adjusted the thickness of the shell parts as needed. The final optimum design resulted in more than 70 percent reduction in mass compared to that of the reference backrest. Moreover, a better close to fully stressed state stress distribution was observed in the two-step optimized backrest.

4.4. Performance of the optimized designs under standard tests

Figures 7 and 8 show the results of the analysis of the optimized Mg alloy backrest under test no. 1 and 2, respectively. For the first test (Fig.7), in the design with initial design variable (values of table 3), the maximum stress occurs at the top corners, along with the inner flange, and at the corners of the fixing joint at the bottom (specified by 1,2, and 3 in Fig.7a, respectively). In this heavy design, these maximum stresses are all well below the AM60 yield stress (16 MPa compared to 124 MPa). By geometrical optimization, the width of the two flanges and that of the lower part are reduced and the maximum stress reaches 64 MPa (Fig. 7b). After shape optimization, the maximum stress reaches 70 MPa (Fig. 7c), a bit higher than that of the first stage, but more uniform stress distribution in the backrest.

As previously mentioned, the second test imposes higher stresses on the backrest compared to the first test. As shown in Fig.8a, the maximum stress in the initial design is 71 MPa and by size and shape optimization, it reaches a value of 124 MPa (Fig.8b and c) which is equal to AM60 yield strength. This could be a good sign of reaching the (near to) optimum point, as the strength constraint is actively satisfied. The maximum overall displacement is also increased from 2.6mm (in the initial design, Fig. 8d) to 5.5mm (size optimization, Fig. 8e) and 6.7mm (shape optimization, Fig. 8f), still accepted an in the standard range [14].

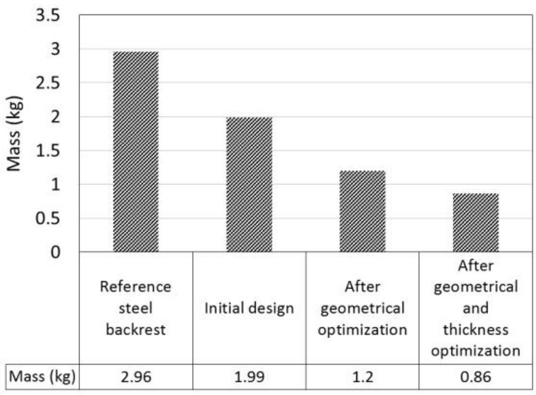

Figure 9: Weight reduction of the backrest from steel to Mg alloy and by two steps of optimization

In Fig.9, the masses of all the studied backrest designs are compared. Results indicate that by changing the reference steel backrest to an initially size-wise acceptable Mg design, there is about 30

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percent mass reduction. However, by size- and shape-optimizing the new design, the reduction rises to about 60 and 70 percent, respectively. This shows the justification for changing the material, the design, and implementing the optimization.

5. Conclusion

In this research, a typical steel car seat backrest as reference was selected and keeping its overall ergonomic outline, a new substitute Mg alloy design was proposed, which benefitted from a simple easy to manufacture Z profile. The two more important standard tests were considered for simulating stress and displacement distributions and further optimizing. Next, considering

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