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An AM-oriented vehicle chassis' A-Pillar Design Approach

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Abstract. Design and production of highly demanding structural systems, such as the chassis, still rely on conventional forming and welding approaches, both because of their proven performance and the economies of scale achieved. Nevertheless, manufacturing of several chassis' segments is also expected to soon gradually switch towards AM, for increased design freedom and optimized performance. This paper proposes an alternative design approach for the A-pillar, a typical passenger car chassis segment; a design suitable in form for AM and equally capable in terms of its dynamic behavior, without undermining the chassis' safety. Prior A-pillar designs along with already published innovative AM-suited design approaches are reviewed. Moreover, these serve as a starting point for an inverse design towards the intended new AM-suited A-pillar alternative. Emphasis is given in the dynamic characteristics of the new structure, through proper modal analysis performed. Finally, the presented research concludes with a scaled-down assessment and verification prototype of the new design, planned to be built via FDM 3D Printing. The prototype is expected to demonstrate primary, as well as secondary/latent benefits from the use of AM in A-pillars, such as the increased diagonal visibility for drivers and passengers, arising from the redesigned, mesh-like form of the segment.

1 Introduction

Additive manufacturing (AM) technologies, commonly known as 3D printing, over the past decade have transformed the potential ways in which products are designed, developed, manufactured and distributed, [1]. For the automotive industry, these advances have opened paths for new designs, lighter, "cleaner", and safer products, shorter lead times and lower costs. Consequently, among other sub-systems and components in the automotive industry, manufacturing of several segments of the chassis is, at some point, also expected to gradually switch towards AM, mainly due to the increased design freedom and optimized performance AM has to offer. However, it is still difficult for AM to compete with

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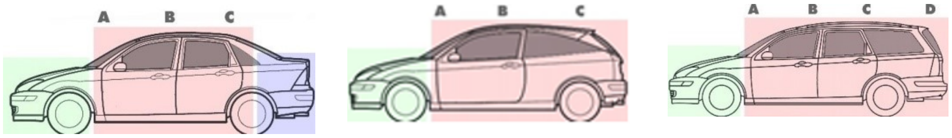
conventional techniques already long in use by automotive companies, that require the highest production rate and repeatability, with the lowest cost and rejection rates possible. Recent international standards (published and/or under development) by ISO & ASTM are clearly aiming in this direction, of appropriate reliability, repeatability, quality, safety and certification of modern AM processes, materials and systems, [2].

In terms of road safety, the occupant cell of a car, which consists of the chassis, is described as a 'survival box' suggesting that the survival of the occupants involved in the circumstance of a traffic accident depend highly on the mechanical response of the cell to the applied loads. The high strength of the occupant cell is a fundamental prerequisite for vehicle safety design, [3]. The chassis and other supporting parts of a vehicle should be designed so as to ensure safety and prevent loss of life in the event of a traffic accident. The chassis of an automobile differs according to its body-shape. Three typical body-shapes are the sedan that has four doors, the lift back that has a rear luggage compartment hatch type door and the station wagon whose roof extends straight back, [4].

As shown in Fig. 1, there are at least three main pillars supporting the frame work of a typical vehicle and these includes A-pillar, B-pillar and C-pillar. In the case of station wagons, that have large passenger compartments, an additional pillar, D-pillar, supports the rear side of the vehicle.



(a) (b) (c)

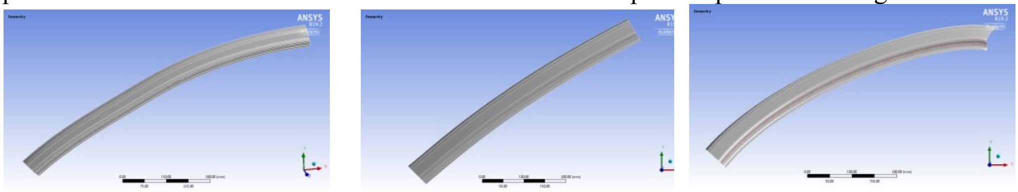
Fig. 1. Typical supporting pillars and their locations in (a) sedan (b) hatchback and (c) station wagon vehicles

A stage during the automobile design is the Body-in-White (BIW). In this stage, the car body is formed by assembled metal sheets, and the main components as chassis, power train, doors, etc. are not still mounted. The determination of the natural frequencies of the parts of the automobile body i.e. the A-Pillar, is crucial in reducing the probability of failure and expanding its life, [5]. An A-pillar is an important load carrying component of any automobile body, [6]. It is a thin-walled construction made of high strength steel alloys which is properly designed and dimensioned in order to successfully withstand the loads developed during a crash or a rollover and meet all the safety requirements. Industrial practice shows that A-pillars by design create large blind spots, blocking the driver's visibility. For this reason, some car-manufacturers attempt to design A-pillars slim and chamfered, to decrease the blind spots to a minimum and improve driver-visibility.

In this paper, three existing A-pillar designs are reviewed in terms of their dynamic behaviour, through modal analysis. Furthermore, an alternative AM-suitable design for the A-pillar is proposed, one that largely comes out of topology optimization and it is compared with a prior published innovative AM-targeted design. Both these designs adopt a perforated-lattice form that directly relates them with AM for manufacturing.

2 A-pillar Design and Modal Analysis

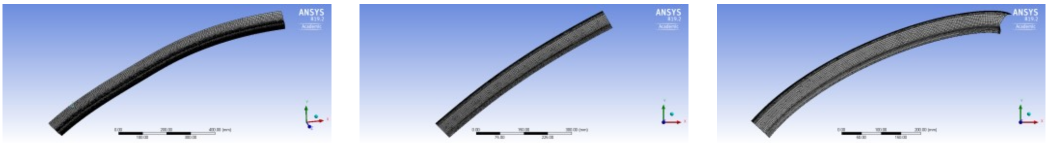
Three A-pillars, each corresponding to each type of an automobile body shape of Fig.1, are investigated and presented in Fig. 2. All 3D Computer Aided Models (CAD) models required were developed on Solidworks ®. It should be noted that they were not based on exact drawings of the vehicles' manufacturers, but on geometrical data retrieved from available online sources, [7, 8, 9]. In order to best approximate the actual geometry of each A-pillar in the simplest possible way in Solidworks, auxiliary lines on a proper reference plane were used, utilizing the overall dimensions of each car model and thus resulting in A-pillars forms of the real scale. The 3D CAD models developed are presented in Fig.2.



(a) (b) (c)

Fig.2. 3D CAD A-pillars of a (a) sedan (M1), (b) hatchback (M2) and a (c) station wagon (M3)

A surface finite element (FE) model has been created for each 3D CAD model in order to perform modal analysis of the three A-Pillar designs. Fig.3 shows the surface FE models.



(a) (b) (c)

Fig.3. FE models of the A-Pillars of (a) sedan (M1), (b) hatchback (M2) and (c) station wagon (M3)

The mesh in all models was uniform, capturing curvature, consisting of FE of type SOLID181. SOLID181 elements are suitable for analyzing thin to moderately-thick shell structures. This element type is four-noded element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z axes, [10]. In all cases the thickness of the A-Pillars is considered equal 1.3 mm. In Table 1, the mass, the number of FE & nodes and the element quality of each FE model are presented.

Table 1. Models' Finite Elements (FE) and Nodes

Model	**Mass (kg)**	**Area (m^2)**	**Number of nodes**	**Number of FE**	**Element Quality**
M1	1.02	0.99	28590	28629	0.82
M2	0.57	0.56	4972	4890	0.78
M3	0.61	0.60	6977	6918	0.79

In Table 1 is obvious that M1 has almost double the surface of the rest, hence it is the heaviest and it consists of more FE and nodes. For all FE models, structural steel has been considered as material, with Young's modulus of 200 GPa, Poisson Ratio of 0.3 and Yield stress equal to 250 MPa.

Modal analysis has been selected in order to assess the dynamic behavior of the A-Pillars, since during the movement of an automobile, the engine cycle incentive and uneven road surface excitation will lead motor vehicles to the forced vibration. If the excitation signal frequency and the resonance frequency of the skin structure is close, the mechanical structure will produce local resonance and high deformation, [11,12]

For the modal analysis, both ends of each A-pillar have been considered fixed, in order to simulate the fact that with a vertical displacement of the chassis its top and bottom will remain untwisted and undeformed. The first six eigenfrequencies for each model are presented in Table 2.

Table 2. A-pillars Eigenfrequencies.

Model	**Eigenfrequencies (Hz)**					
	1st	**2nd**	**3rd**	**4th**	**5th**	**6th**
M1	107.67	147.41	190.92	275.61	312.88	389.10
M2	230.02	317.00	334.96	584.388	717.94	841.12
M3	139.16	248.89	338.63	449.63	564.26	650.92

In Fig.4 the contours of total displacement in the first three eigenfrequencies are presented for each FE model.

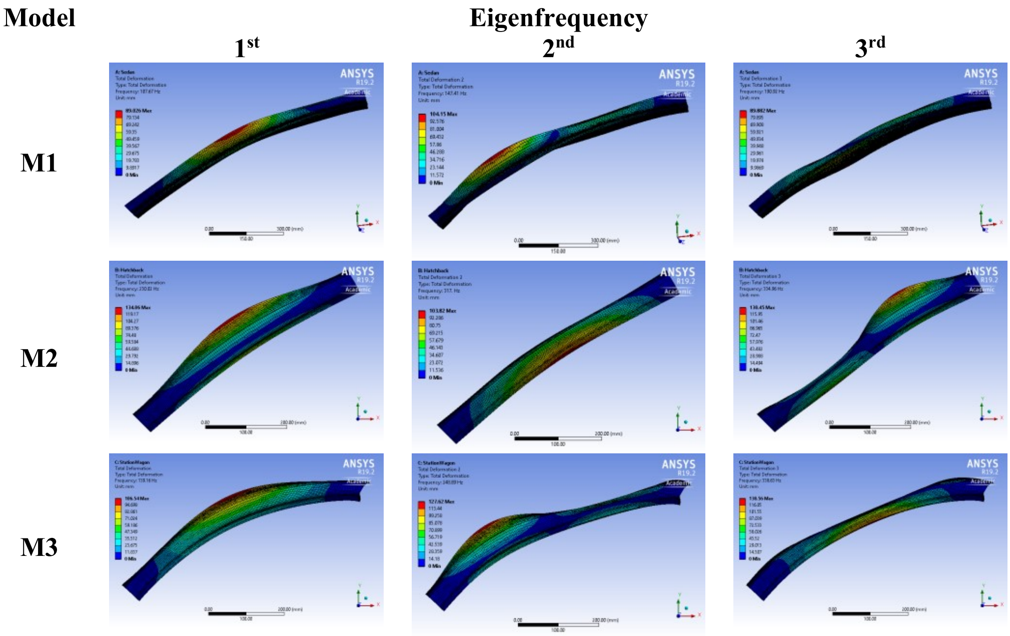
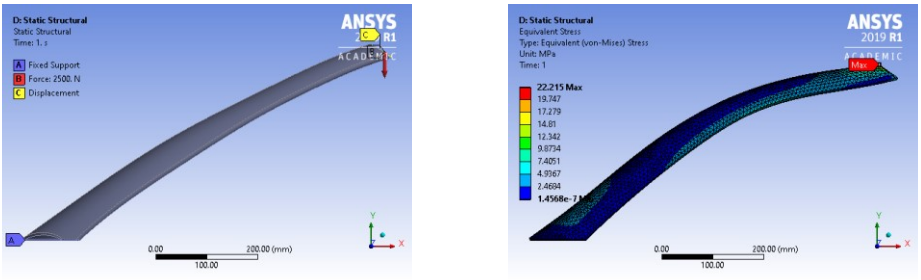


Fig.4. Total displacement for eigenfrequencies 1st, 2nd and 3rd in M1, M2 and M3

In Table 2 is obvious that M1 has the lowest eigenfrequencies, while M2 the highest. On the other hand, the displacement for the first eigenfrequency is highest for M2 (134 mm) while for the second and the third one is highest for M3 (128 mm and 131 mm, respectively).

3 M3 A-Pillar Topology Optimization

For the M3 model also an alternative, perforated, AM-suitable design exists. This design is compared to a design produced with topology optimization in a static structural loading simulating rollover. In more details, Ansys Workbench 2109R1 has been performed on a solid body corresponding to the M3 structure. The boundary conditions, along with the equivalent Von Mises Stress (VMS) contour are provided in Fig. 5. The force has been calculated in order to simulate rollover (vehicle's curb weight with one passenger 1500 kg).

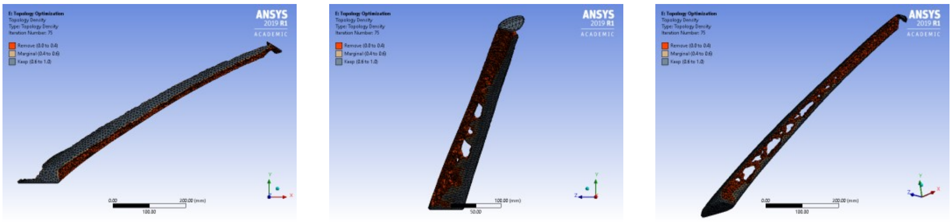


(a) (b)

Fig. 5. (a) Boundary conditions and (b) equivalent VMS contour of the static analysis of M3

In Fig. 5 is obvious that the highest value of equivalent VMS is 23 MPa, which is lower than the yield stress of the material.

For the Topology Optimization the Sequential Convex Programming solver has been used. Weight minimization has been set as objective function and maximum stress (yield stress of the structural steel) as the constraint. The optimization procedure converged after 75 iterations producing a structure with a weight of 4.80 kg. In Fig. 6 the result of the topology optimization is presented.



(a) (b) (c)

Fig. 6. Optimized structure for the M3 model in (a) front, (b) right and (c) arbitrary view

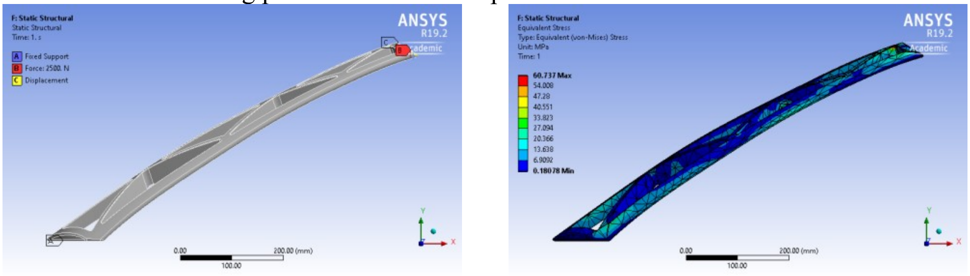
As mentioned above, the provided new structure is similar to a perforated A-pillar design (M3p) originating from M3 developed by the car manufacturer, in order to improve driver visibility. The perforated form characterizes both designs as candidate for AM. In Table 3 the result of the modal analysis of this A-Pillar (M3p) is presented.

Table 3. A-pillar Eigenfrequencies.

Model	**Eigenfrequencies (Hz)**					
	1st	**2nd**	**3rd**	**4th**	**5th**	**6th**
M3p	266.85	492.82	612.12	656.20	703.91	731.96

Comparing the values of the eigenfrequencies in Table 3 with these in Table 2 is obvious that M3p model has lower values than M3, but still, higher than M1 and M2.

In Fig. 7 the boundary conditions and the results of the static analysis simulating rollover for the existing perforated model are presented.



(a) (b)

Fig. 7. (a) Boundary conditions and (b) equivalent VMS contour of the static analysis of M3p

4 Conclusion

In this paper, three A-pillars (M1, M2, M3), each corresponding to a characteristic type of an automobile body shape, are designed in Solidworks and their dynamic behavior has been investigated through modal analysis in ANSYS. Furthermore, an alternative for the M3 model has been created using topology optimization. This design was compared to an already existing perforated design (M3p) in a static structural loading simulating rollover. The perforated form characterizing both designs makes them candidates for AM. In the future both these designs will used to create scaled down prototypes with AM in order to experimentally test their performance.

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