Numerical Study of Automotive Doors

Said Darwish, H. M. A. Hussein and Ahmad Gemeal

***Abstract*—Cars have various types of doors. The swinging doors which are the most common are almost the most complicated parts in a car since they not only determine the general guidelines of car style, but also are vital for passenger's safety by protecting humans from side crashes. Comparison between FEA results and targets led to the necessity to split lower opening of front door into two parts to increase stiffness. Also, thickness of window regulator engine fixing in both front and rear doors are increased. Predetermined values from previous works conducted on a similar existing SUV vehicle were used as targets to be achieved by Finite Element Analysis (FEA) of car doors. Mobile hinge fixing is duplicated for both front and rear doors Inner panel opening in front door window lower mechanism are also decreased.**

***Index Term*— Finite element analysis, Car door, Door sag/modal analysis, static analysis.**

I. Introduction

FEA is based on various formulations [1]; checking up numerical methods used is essential for estimation of validity of results [2]. FEA is a powerful computational tool for analyzing complicated structures like doors. If it is compared to experimental work, it saves much time and costs. Various types of tests are essentials for door design [3]. Firstly, NVH analysis which is noise, vibration and harshness analysis to detect natural frequencies, must be performed to give general outlook about stiffness in the doors, to check whether each door fulfill the predetermined targets which came from a similar designed car.

The dynamic modal analysis entailed determination of the lowest natural frequency of the car door. This was accomplished by using the Lanczos algorithm, an iterative algorithm that is an adaptation of power method for finding eigen-values and eigen-vector of a square matrix or the singular value decomposition of a rectangular matrix [4]. The power method is first used for finding the largest eigen-value of a matrix. After the first eigen-vector/value is obtained, the algorithm is successively restricted to the null space of the known eigen-vectors to get the other eigen-vector/values. In practice, this simple algorithm does not work very well for computing a large number of the eigen-vectors because any round-off error will tend to degrade the accuracy of the computation. Also, the basic power method typically converges slowly, even for the first eigen-vector. Lanczos algorithm is a modification of the basic power algorithm in which each new eigen-vector is restricted to be orthogonal to all the previous eigen-vectors. In the course of constructing these vectors, the normalizing constants used are assembled into a tri-diagonal matrix whose most significant eigen-values quickly converge to the eigen-values of the original system [5].

The NVH requirements for the car door were defined by determining the lowest natural vibrational frequency for the door in the close position [6]. Toward that end, an eigen-value analysis of the closed car door was conducted and the eigen-modes and their corresponding eigen-frequencies were obtained using the Lanczos numerical eigen-solver.

NVH is not only for that checks, but also essential for checking FE mesh and revealing any improperly attached part in the body, because the number of natural frequencies depends on number of free bodies in the system.

Secondly, static analysis which is test of strength of car doors by applying forces at carefully selected points in various components of each door for extracting the displacement and stresses results. This can also be divided into global stiffness FEA and closure stiffness FEA. In the former, the effect of force on the whole door is analyzed while in the later, certain closures in the door are analyzed. Stress results are compared with elastic limit of the material of the component. It must be lower than it with a certain factor of safety. Displacement results are used for calculating stiffness of the component at a specified point through dividing the applied force with resulting displacement and the calculated stiffness values are compared to target. If results of some tests do not match targets, modifications must be suggested to some components such as web addition or component thickness increasing or some related parameters changing. Any suggestions must be thoroughly studied since it may affect other criteria i.e. increase overall car weight or decrease stiffness of some other parts. Test must be performed several times to verify validity of the suggested modifications until matching targets is reached all over the door.

Mesh was made by Hypermesh 8 [7] according to general rules of meshing: elements must be of global size 8 mm and

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not to exceed 16 mm. Elements are of shell elements, quadratic but triangular elements are allowed such that not to exceed 10% of number of elements. Meshing was made roughly at first and it was refined step by step till it reached an optimum. Numbers of nodes, elements and other statistics are shown in Table 1 while Figure 1 illustrates components of doors that were used in it. Connections between various components are achieved by modeling of arc welding mechanical fixations by rigid bars [8] while spot welding is modeled as CWELD modeling in NASTRAN [9]. Numbers of elements, cweld, rigid bars and spiders used in each door are shown in Table 3.

TABLE I
General statistics of mesh of car front and rear doors

	Front doors	Rear doors
No.nodes	39858	50500
No. elements	37641	48171

TABLE II
Connectors statistics of front and rear doors

	Front door	Rear door
Spot weld	624	436
Rigid bars	64	53
Spiders	15	12

Forces and boundary conditions were inserted to the resulted mesh according to each case as discussed below and analysis was carried out by MD. Nastran R3

Modeling of spot welding in FEA generally and in Nastran specially passed through several steps [9-10].Cweld were performed according to general guidelines [10], Taking into consideration its behavior under dynamic analysis [11], and strength under various loadings [12],

Materials of door components are given in Table 3. Problems; revealed by the FEA; are treated mainly by changing designs e.g. decrease an opening, duplicating hinges, but modifying material remains an option. Strength to weight ratio of both doors components still has an opportunity to be increased by changing material used. Checking of material used was carried as shown Table 4. In which it is noticed that the highest strength steel used is steel 42 and its weight percentage to all door material is 25%. That means that, from strength point of view, there is still wide opportunity to decrease total door weight [13]. This can be achieved by changing material of door components to ultra light steel [14] [15].

TABLE III
Components statistics of front door

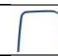
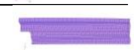
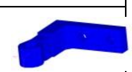
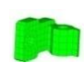
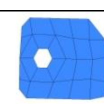
						Front door
No.	Name	Mat.	No. off	Th. mm	Mass (kg)	image
1	Hinge reinforce ment	St 42	1	1.2	1.25 5	
2	Intrusion bar bracket (up.&Lo w)	St 42	2	1.2	0.23 4	
3	Intrusion bar	St 42	1	1.2	1.21	
4	Latch reinforce ment	St 27.5	1	1.2	0.42 7	
5	Window regulator main bracket	Low carbon steel 04	1	1.2	0.31 3	
6	Window sash	St 27.5	1	0.8	0.6	
7	Outer Belt line	St 42	1	0.8	1.05	
8	Inner Belt line	St 42	1	1.2	1.02 3	
9	Outer Belt line reinforce mt	St 27.5	1	0.8	0.58	
10	Outer panel	Low carbon steel 04	1	0.8	6.3	
11	Inner Panel	St 27.5	1	0.8	6.55	
12	Window regulator auxiliary bracket	Low carbon steel 04	1	1.2	0.07 6	
13	Handle bracket	Low carbon steel 06	1	0.8	0.01 3	
14	Fixing hinge	St 27.5	2	Solid elem ent	0.5	
14	Mobile hinge	St 27.5	2	Solid elem ent	0.41 8	
15	Hinge reinforce ment plate	Low carbon steel 04	2	1.2	0.04 32	
16	bracket	Steel27 .5		1		
	Total				20,5 9	

TABLE IV
Components statistics of rear door

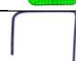
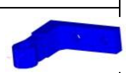
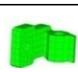
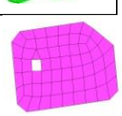
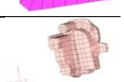
						Rear door
No.	Name of compo-nent	materi-al	No off	Th mm	Mass kg	image
1	Hinge reinforce ment	St 42	1	1.2	1.55	
2	Intrusion bar bracket (up.&Low)	St 42	2	1.2	0.255	
3	Intrusion bar	St 42	1	1.2	0.538	
4	Latch reinforce ment	St 27.5	1	1.2	0.58	
5	Window regulator main bracket	Low carbon steel 04	1	1.2	0.25	
6	Window sash	St 27.5	1	0.8	0.61	
7	Outer Belt line	St 42	1	0.8	0.68	
8	Inner Belt line	St 42	1	1.2	0.57	
9	Outer Belt line reinforce mt	St 27.5	1	0.8	1.23	
10	Outer panel	Low carbon steel 04	1	0.8	6	
11	Inner Panel	St 27.5	1	0.8	6.4	
12	Window regulator auxiliary bracket	Low carbon steel 04	1	1.2		
13	Handle bracket	Low carbon steel 06	1	0.8	0.367	
14	Fixing hinge	St 27.5	2	Solid element	0.5	
14	Mobile hinge	St 27.5	2	Solid element	0.418	
15	Hinge reinforce ment plate	Low carbon steel 04	2	1.2	0.056	
16	bracket	Steel27.5		1	0.3	
	Total				20,6745	

TABLE V
Material statistics of car front and rear doors

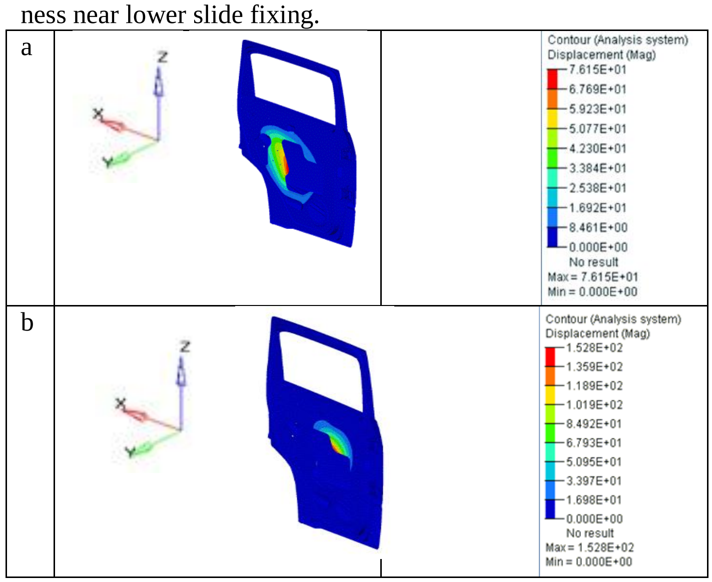
	Front door		Rear door	
	mass kg	mass %	mass	mass %
Low carbon steel 04	6,42	32	6,056	29.6
Low carbon steel 06	0.01	0	0,367	1.8
St 42	4,77	24	3,6635	17.9
St 27.5	9,08	45	10,338	50.61
	20,59		20,6745	

2. WORK AND DISCUSSIONS

2.1 Dynamic modal analysis

2.1.1 Front Door

It is shown in Figure 2 the first two modes that are local modes while the second two modes are global modes. The local modes are shown in Figure 2 a, b with natural frequencies 20.15 and 44.12 Hz respectively and oscillates mainly inner surface while the global modes are shown in Figure 2 c and d, natural frequencies 49.45 (target >47Hz) and 66.75 Hz respectively and oscillates mainly outer surface of the door. The first mode of the global modes is out of target and so, indicates that it needs to increase its stiffness as shown in exaggerated area in Figure 2 a. This can be achieved by inserting metal partition inside the opening, to increase the local stiffness near lower slide fixing.



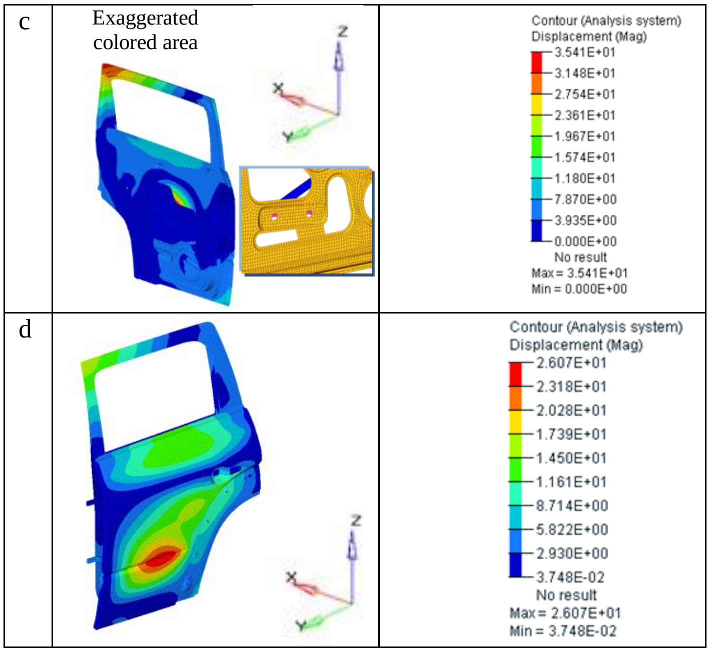
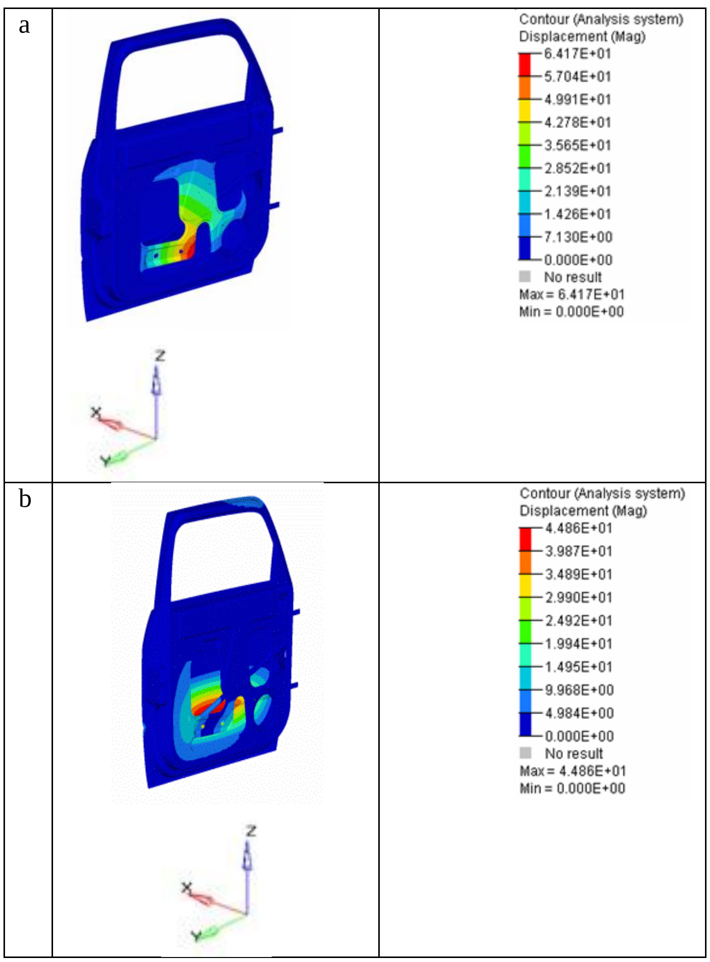


Fig. 1. FE dynamic modal analysis of rear door



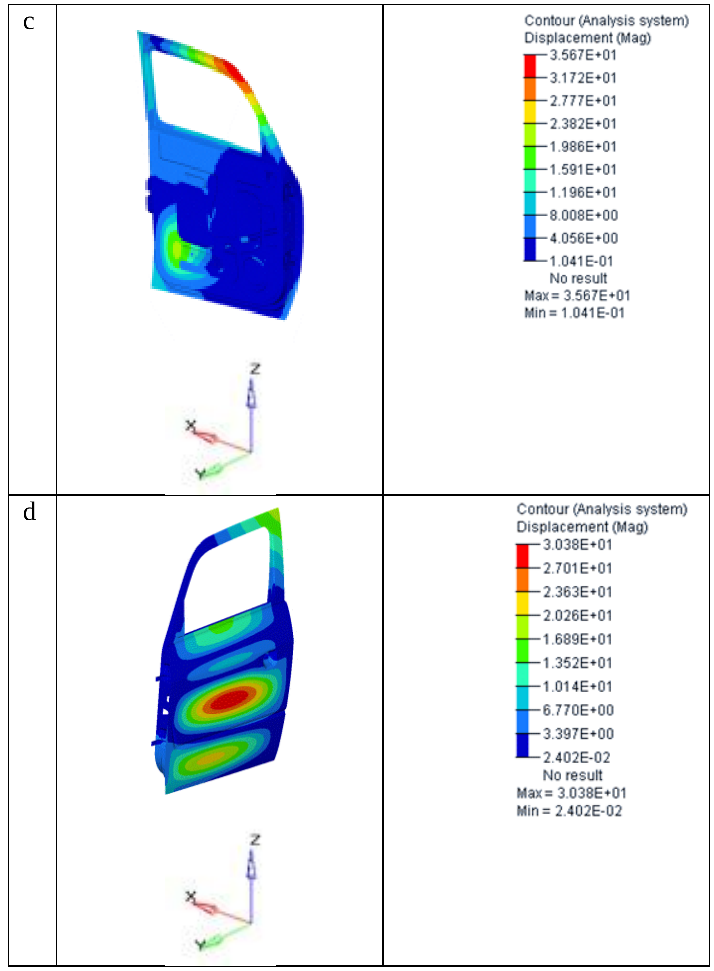


Fig. 2. FE dynamic modal analysis of front door frequencies: a 27.36 Hz, b 38.37 Hz, c 45.7 Hz, d 66.65 Hz

2.1.2 Rear door

Figure 3 shows FE dynamic modal analysis of rear door which detected frequencies: 27.36 Hz, 38.37 Hz, 45.7 Hz and 66.65 Hz. The first two modes are local modes while the second two modes are global modes. The local modes are 27.36 and 38.37 Hz oscillates mainly inner surface while the global modes are 45.7 (target >47Hz) and 66.65 Hz oscillates mainly outer surface of the door. They all achieved targets.

2.2 Static Analysis

2.2.1 Global Analysis

a) 2.2.1.1 Lateral stiffness analysis

It depends on boundary conditions of constrains type 12356 (means that translations are prevented in x, y, z directions and rotations are prevented in xy, xz, yz planes) at hinges and so hinges mechanism is free to rotate around its own axle and constrain type 123456 at latch. A lateral load of 200 N in y direction is applied on upper right and left points. Keeping the same boundary conditions, a lateral load of 100N applied inward and outward the car on the beltline. Boundary conditions and loadings are shown in Figure 4 Displacement distributions due to various cases are shown in Figure 5. Stress distributions due to various cases are shown in Figure 6. The displacements at loading points and maximum stresses are extracted and tabulated in Table 6 Numerical results of FE analysis of front and rear door. Numerical results of FE analysis of front and rear doors are within the elastic stress limit (assuming steel of strength 275MPa) mean they are safe except the row of stresses due to vertical displacement, this is discussed in section 2.2.1.2. Front door analysis achieves targets. All values achieve targets except the vertical displacement; front glass and window lower mechanism slide are exceeded. Rear door stress analysis suggests the need to extend the latch reinforce or adding a terminal flange in this area.

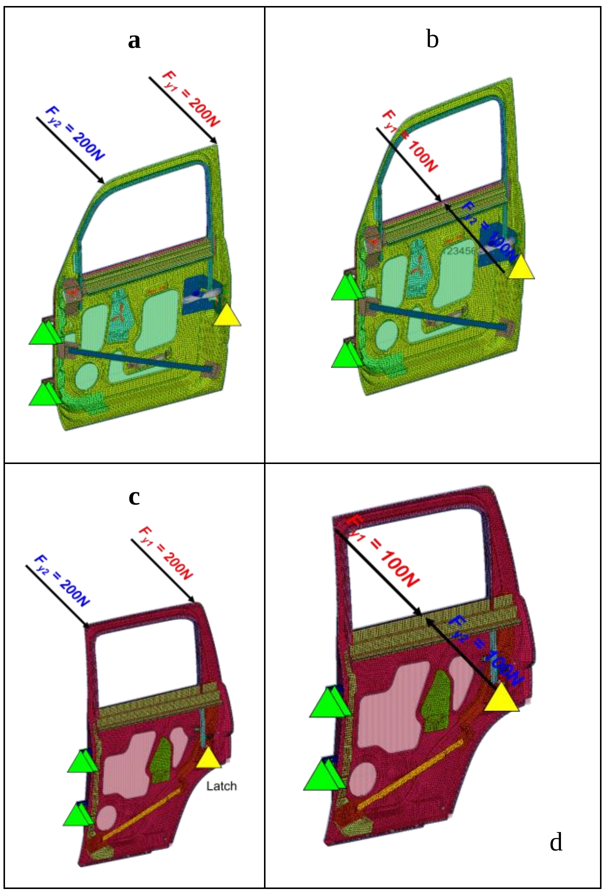
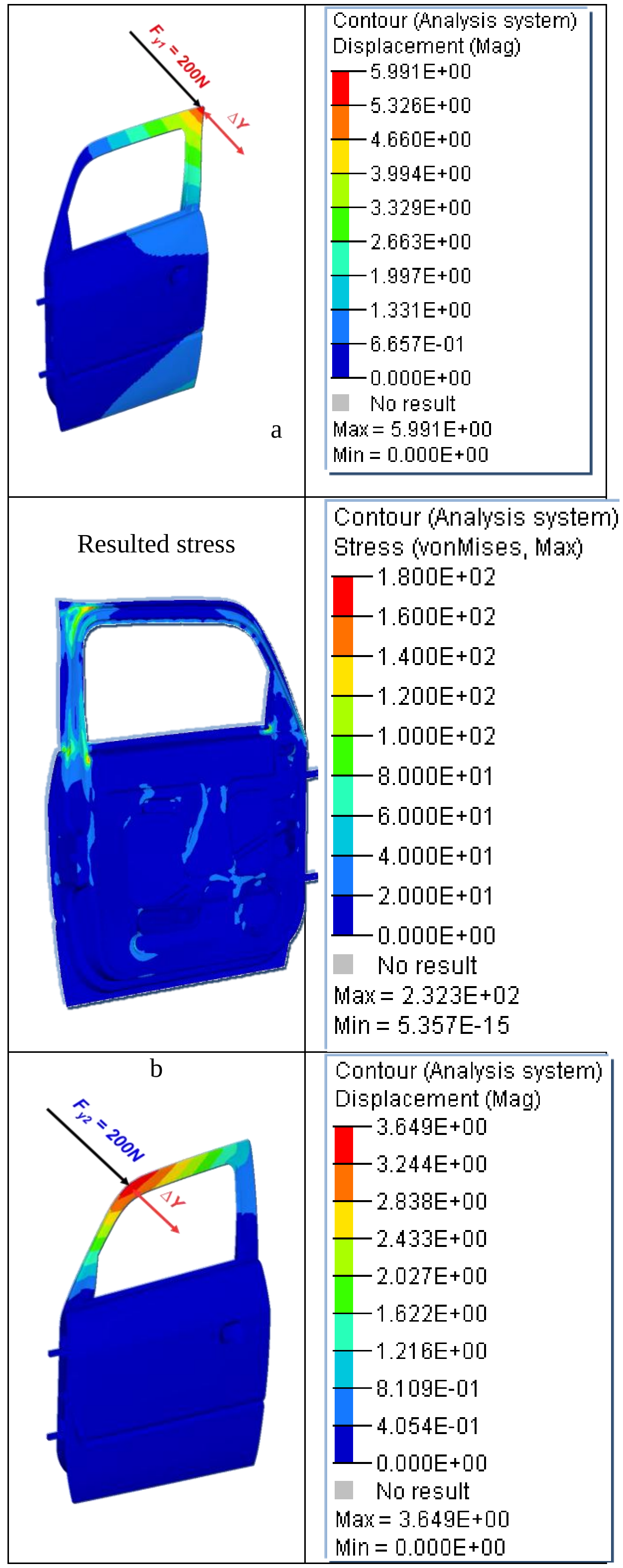
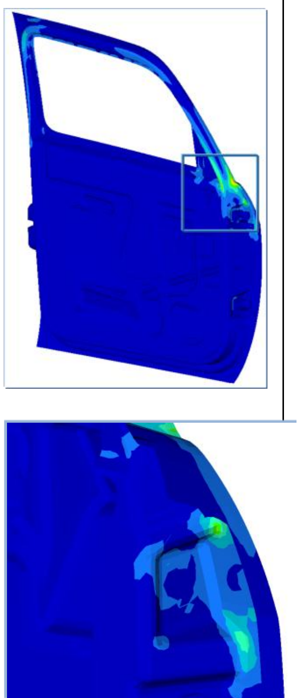
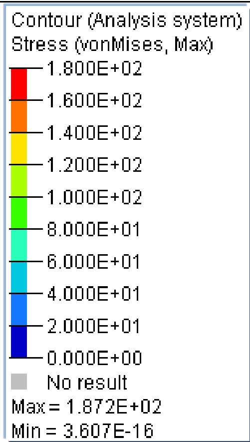


Fig. 3. Boundary conditions and loadings of front and rear doors (shows lateral and beltline transverse loadings, a ,b also the same for rear door lateral and beltline transverse loadings. a,c and b,d are the 1st and 2nd load conditions respectively, represents constraints 12356, constraint 123456



Resulted stresses





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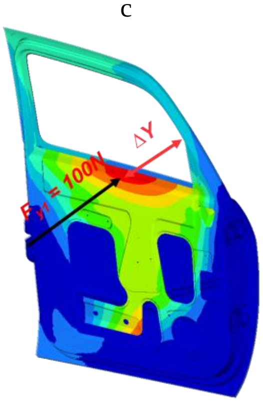
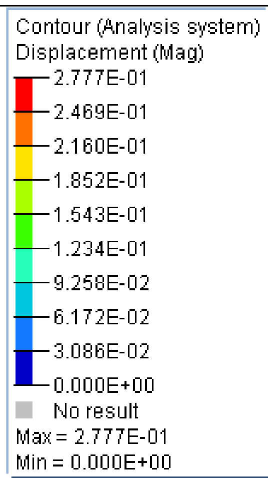
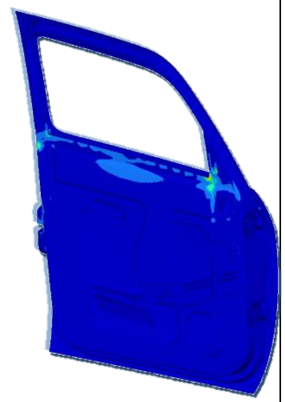
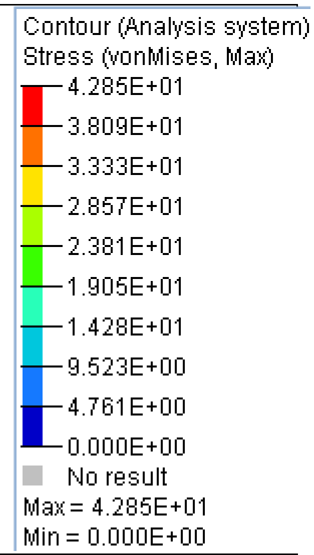




Resulted stresses





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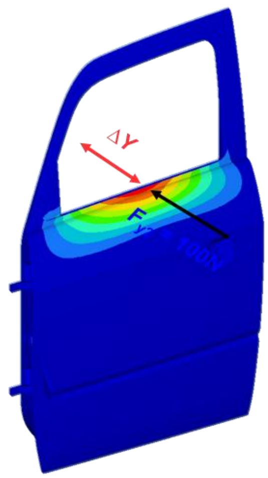

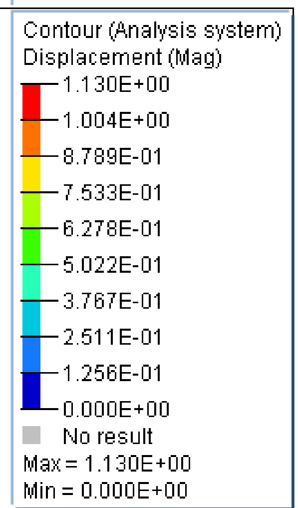

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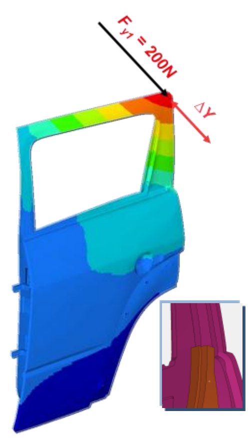

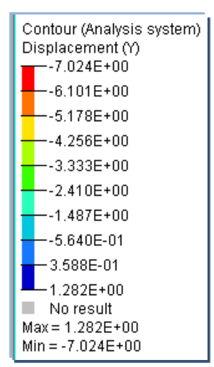

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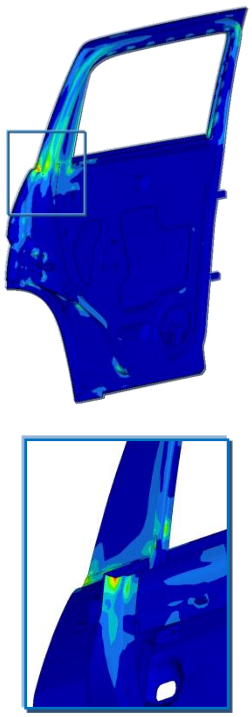
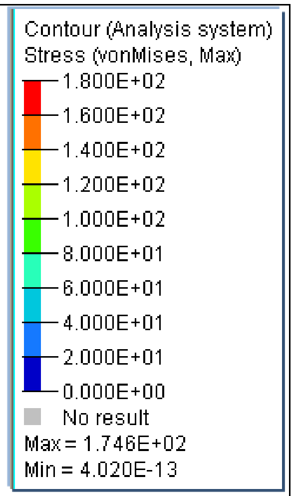
Resulted stresses





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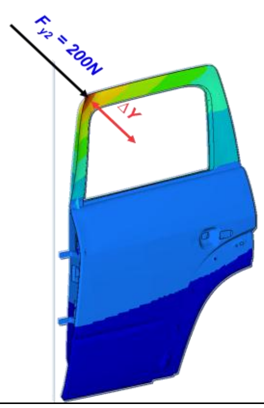
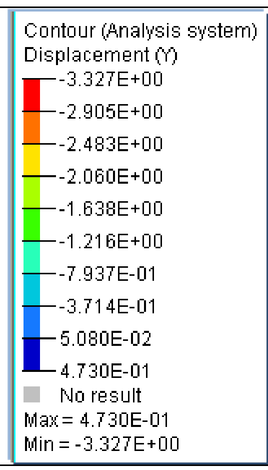
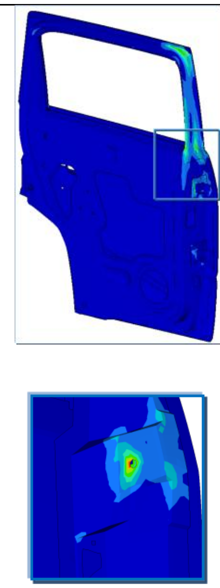
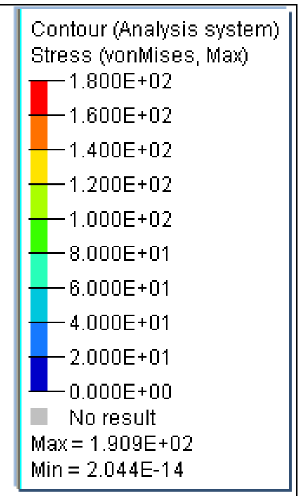
1st load condition

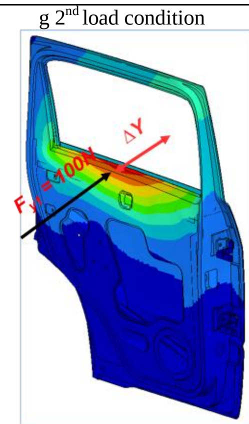


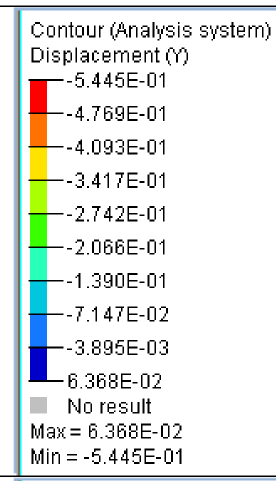


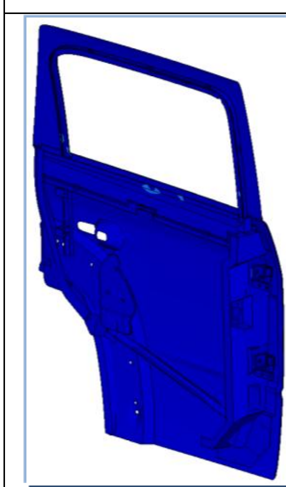


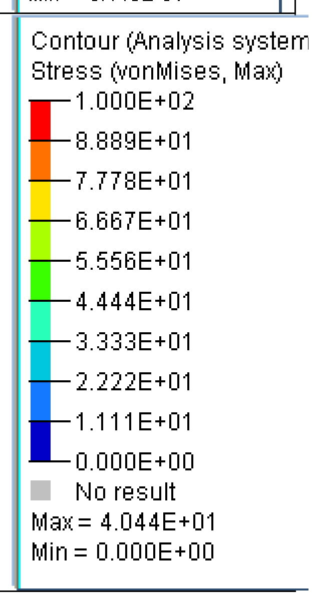


g 2nd load condition









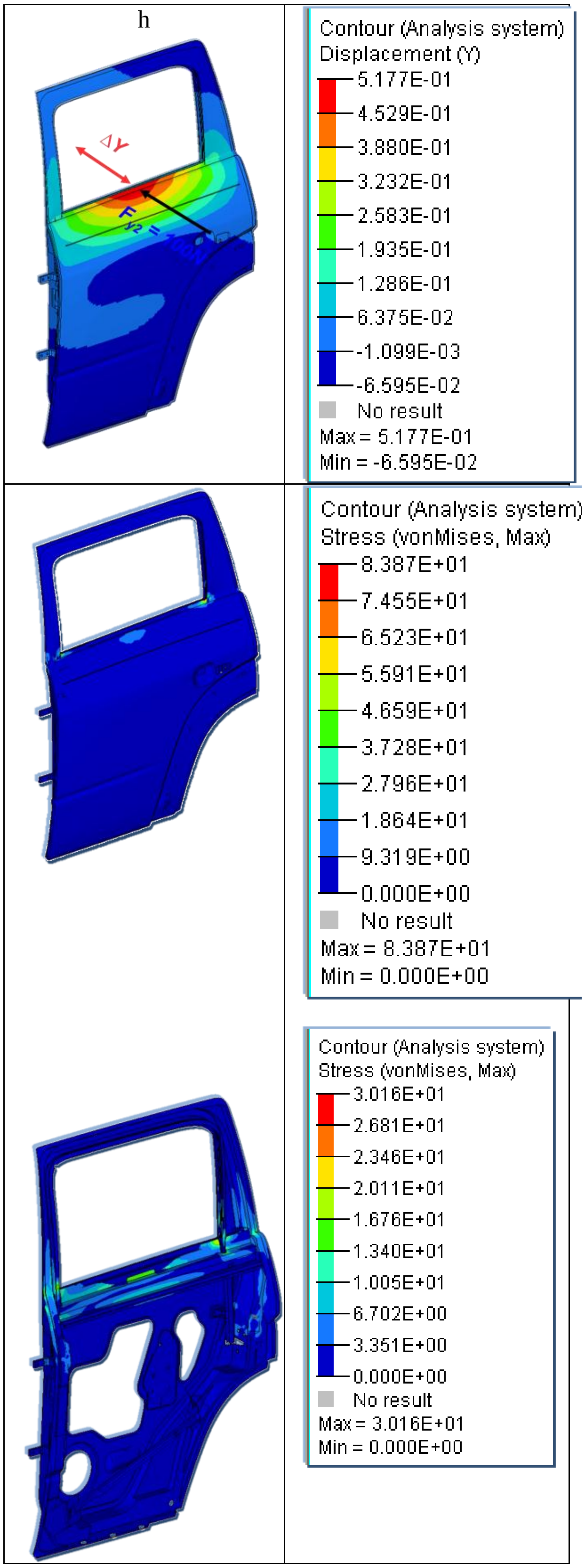


Fig. 4. FE Lateral displacement and stress distribution results for front and rear doors, for each load case

2.2.1.2 Sag analysis

The front or rear door is fixed by fixing hinge of constrains type 123456 and fixed on latch by constrain type 2. A vertical load of 500 N in Z direction is applied on latch. Hinges mechanism is fixed around its own axle. Displacement on the loaded point for front door is 1.85 mm while for rear 4.17 mm (target < 5.0mm), as mentioned in Figure 6 so it is safe for front door but too close to target for rear door. Max. stress for front door is 292 MPa and for rear door is 375 MPa which exceeds the elastic stress limit (assuming steel of strength 275 MPa). This is shown in Figure 7 and it is suggested to duplicate the mobile hinge fixing. In both doors, A quick modification of hinge fixing in rear door decreased stress to 280 MPa this and new stress distribution are shown in Figure 9. It is noticed that vertical stiffness in rear door is much lower than that of front door. Comparison between meshed front and rear doors as shown in Figure 8 indicates that the anti-intrusion bar in the rear is shorter than that of front door and that there is mirror reinforcement for front door that increases stiffness while no such reinforcement exists for rear door. Comparison with Figure 7 shows that stress became 180 MPa

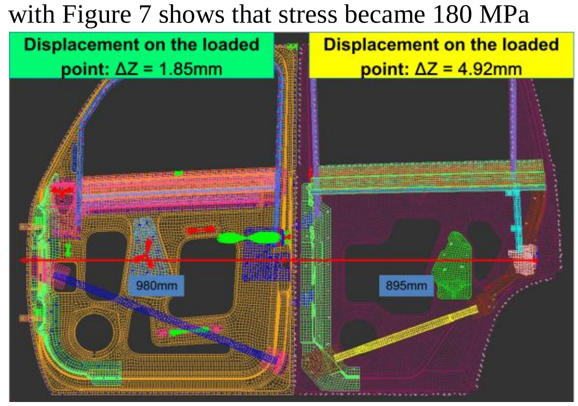


Fig. 5. Meshed front and rear doors for comparison

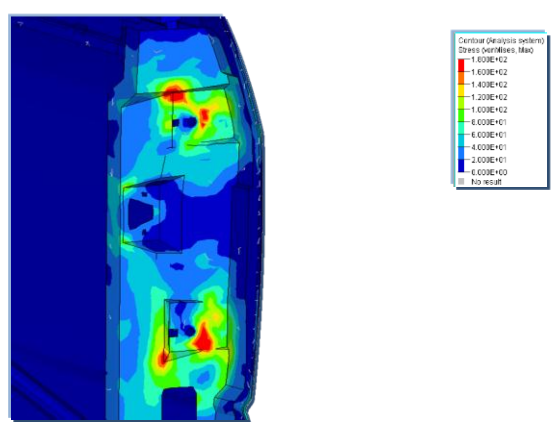
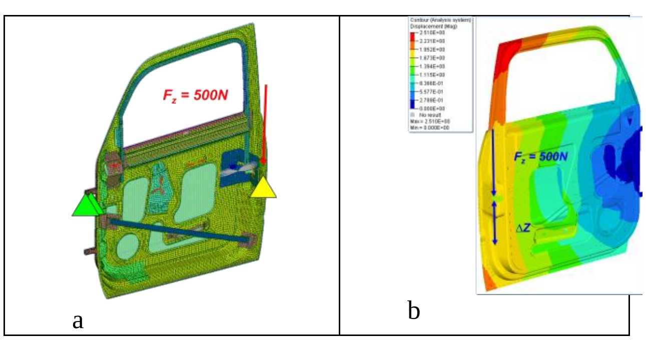


Fig. 6. Von Mises contour map after duplicating the hinge fixings

TABLE VI
Numerical results of FE analysis of front and rear door

		Front door				Rear door			
	Loading type	Resulted lateral displacement at loading point Dy (mm)	Target (mm)	Results Maximum stress (MPa)	Target (MPa)	Resulted lateral displacement at loading point (mm)	Target (mm)	Resulted Maximum stress (MPa)	Target (MPa)
Upper edge	Right	5.46	<7	232	<275	6.76	<7	174	<275
	Left	3.48	<7	187	<275	2.98	<7	190	<275
Belt line	inward	0.26	<1.2	43	<275	0.52	<1.2	40	<275
	outward	0.96	<1.2	63.5	<275	0.5	<1.2	83.8	<275
		Vertical displacement Dz(mm)		Resulted stiffness (N/mm)	Targeted stiffness (N/mm)			Resulted stiffness (N/mm)	Targeted stiffness (N/mm)
Vertical loading		1.85	<5	270	100	4.17	<5	120	100
Max. stress				292	275				



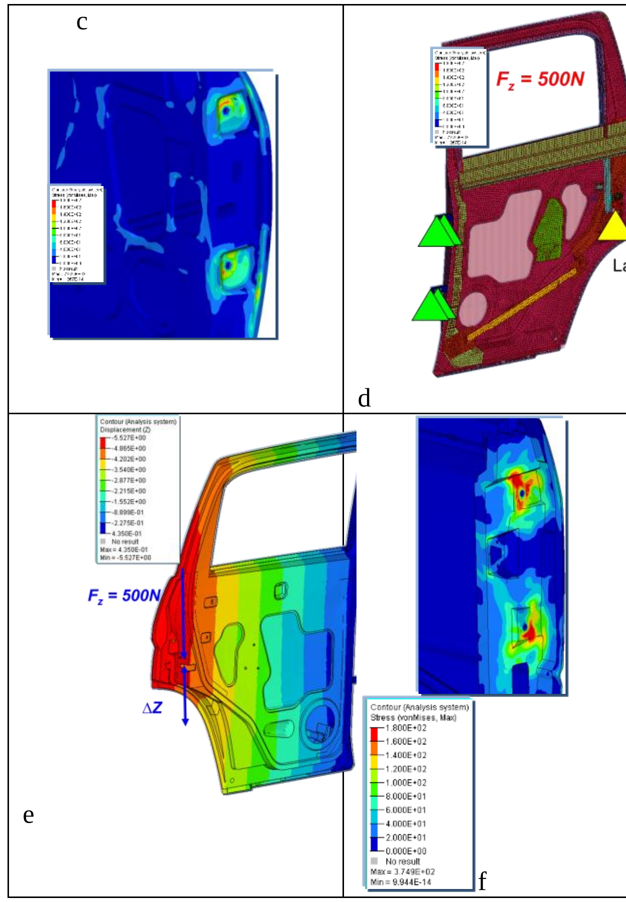


Fig. 7. FEA results of front door under 500 N vertical load,a, boundary conditions and loading, , resulted stress distribution, c hinge area exaggerated, rear door, e boundary conditions and loading, f resulted stress distrib, constraint 2, ution, g hinge area exaggerated, ▲ constraint 123456▲

2.2.2 Local analysis

Load points applied as shown in Figure 9 and constraints type 123456 was located on latch, hinges and in the lower and upper line of the door. This analysis led to several conclusions mentioned below. The resulted displacements, maximum stresses and vertical stiffnesses for both front and rear doors in various cases are shown in Table 7and Table 8, which shows that they all achieve targets except that the rear lateral loading condition of rear door the resulted displacements are too close to target.

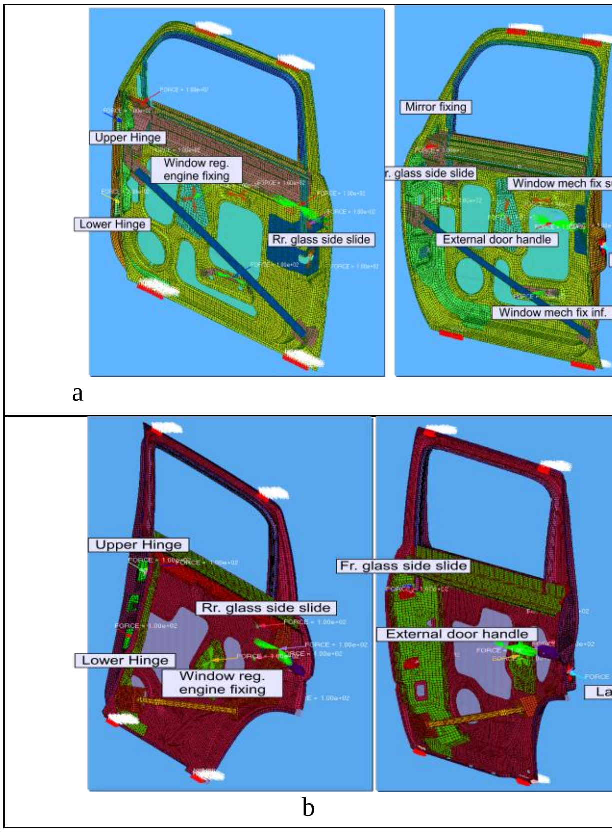


Fig. 8. Boundary conditions used in front and rear doors closure local analysis

TABLE VII

Front door local analysis results, load 100 N

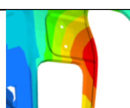
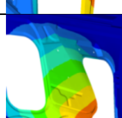
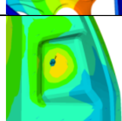
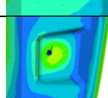
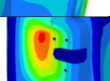
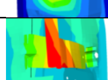
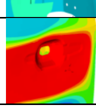
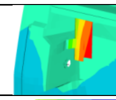
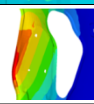
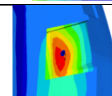
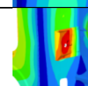
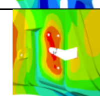
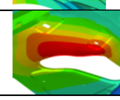
	Front door				
Name		Dir	Displ. mm	Stiff. N/mm	Target (mm)
Front glass side slide		Y	0.76	132	>100
Window regulator engine fixing 1		Y	3.08	32	>100
Upper Hinge		N	0.023	4348	>100
Lower hinge		N	0.021	4762	>100
Latch		N	0.063	1587	>100
Rear glass side slide		Y	0.44	227	>100
External door handle		Y	0.45	222	>100

TABLE VIII

Rear door local analysis results, load 100 N

	Rear door				
Name		Dir	Displ. (mm)	Stiff. (N/mm)	Target (mm)
Front glass side slide		Y	0.45	222	>100
Window regulator engine fixing 1		Y	6.39	16	>100
Upper Hinge		N	0.072	1389	>1000
Lower hinge		N	0.06	1667	>1000
Latch		N	0.041	2439	>300
Rear glass side slide		Y	0.61	164	>100

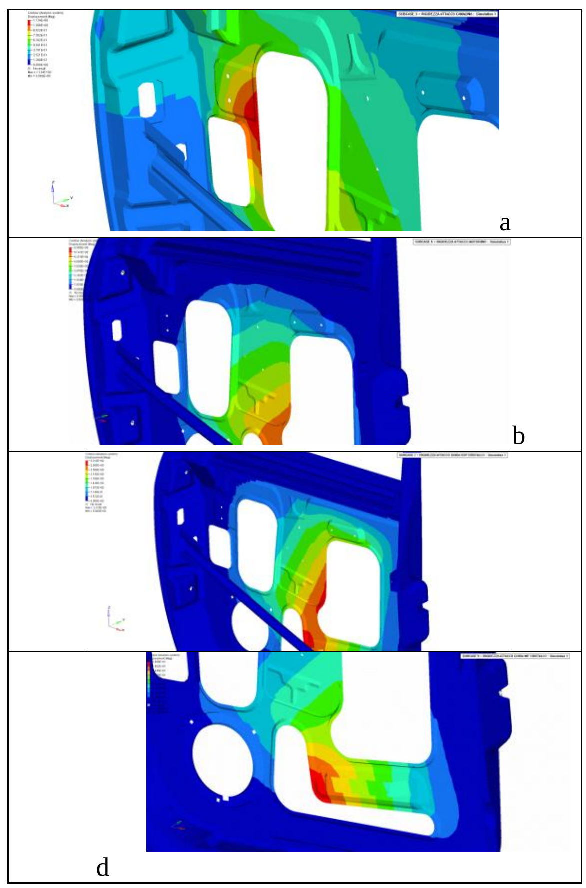


Fig. 9. Finite element closure analysis, a stress distribution in front glass side, b window regulator engine fixing; subcase 5 simulation 1, c,d window upper and lower fixing mechanism

CONCLUSIONS

1. Rear Modal analysis of rear and front doors reveals that they is in target;
2. All values in rear door global stiffness and local stiffness analysis and for the vertical displacement analysis are much better than targets except for the lateral displacement stiffness analysis of window regulator engine fixing that is only just in target; its local reinforce should be brought to 1.2 mm and elongated upperward. Also, the inner panel opening in this area should be locally reviewed.
3. All values in front door global and lateral stiffness and vertical displacement analysis are much better than targets except that the inner panel should be less opened around and window regulator engine fixing where the local reinforce must brought to 1.2 mm and the inner panel should be less opened around. Also, upper window mechanism where the local engine fix reinforce must be brought to 1.2 mm and inner panel should be less opened around. Lower window mechanism is very far away from the target, Inner panel opening must be reviewed in this area;
4. Front door lower opening must be split into two;
5. Rear door stress analysis suggests the need to extend the latch reinforce or adding a terminal flange in this area.
6. Anti-intrusion bar and mirror reinforcement increases stiffness in the hinged area for both front and rear doors rather than for rear door only;
7. From strength point of view: there is still wide opportunity to increase stiffness of doors by increasing percentage of St. 42 already used and/or other steels of high strength without increasing weight.

FUTURE WORK

It is recommended that structural analysis optimization of doors to be made.

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