A Study on Joint Stiffness of a Typical BIW Structure to Qualify Its NVH Behavior

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Abstract— In the automotive industry, noise and vibration of vehicles play an important role in environmental noise pollution and comfort of the driver and passengers since it affects the overall performance of the vehicle. Hence an effort is made to bring down the Noise, Vibration and Harshness (NVH) characteristics at early design stages. One of the considerations for better NVH behavior is the stiffness properties at critical joints in a body-in-white (BIW). Stiffness values at different joints plays an important role in the NVH characteristics of a BIW structure of an automobile. The stiffness values are used to study the NVH characteristics of the vehicle.
Also, the displacement values at different joints are obtained from the analysis and plotted along the length of the vehicle. In general the vertical displacements at different joints need to be more or less the same or the mobility curve more or less a straight line, for qualifying good joints in the vehicle. In general, adequate joint stiffness results in better NVH behavior. The objective of this paper therefore, is to evaluate the joint stiffness analysis of critical joints of a typical BIW of a car under bending and torsional loads to assess its NVH behavior.

Index Terms— NVH, Joint Stiffness Analysis, Mobility curve, Specific stiffness of joints

1 INTRODUCTION

WHEN designing a car body various important factors such as crashworthiness, durability, ride quality, aesthetics, aerodynamics are considered. NVH (Noise, Vibration and Harshness) is a major factor associated to ride quality wherein the joints contribute to the NVH performance of vehicle. NVH is a stiffness proportional property. Hence joint stiffness of the BIW is an important step towards improving the overall NVH performance of the car. Even then, the research on the design of joints and the influence of joint structures on NVH is limited.

In addition, the mobility curve can be plotted using the displacements obtained at the joint. The curve should be more or less a straight line to have a good NVH performance from the joints. High variation of relative displacements of the joints indicate instability which is expected to attenuate the noise levels. The high displacement or peak values at a particular joint or joints can be brought down by improving the joint stiffness. Improving the joint stiffness can be done either by changing the material of structure or by changing the geometry or by a combination of both.

Historically, NVH was not considered as an important parameter in the design of vehicle. Over the years, it has gained importance and now it is one of the major factor considered in designing vehicle to customer satisfaction. The first NVH tests were carried only to reduce the engine and powertrain noise but now other contributors such as road noise, wind noise, body design, interior acoustics and many more are taken into account. A lot of research is being done to keep the noise and vibration levels to a minimum [1], [2].

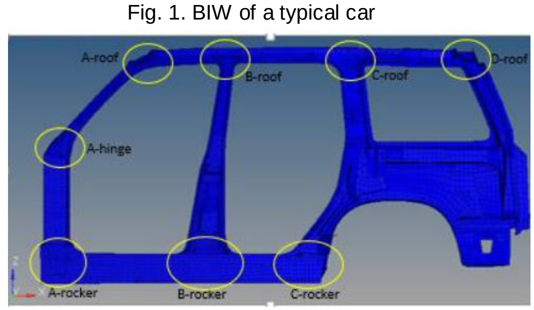
The inside of the BIW of a typical car used to be hollow. To improve the stiffness, the thickness of the body used to be varied to bring the noise and vibration down. Over a decade, the hollow BIW is filled with polyurethane foam (PU) to improve the structural stiffness and hence the NVH performance [4], [5]. This forms the basis for the present paper which involves a systematic joint stiffness analysis (JSA) of BIW to improve the NVH performance by varying the material and geometrical properties including inclusion of PU foam.

2 METHODOLOGY

Starting from the BIW model of a typical car, the model is meshed with 2D shell elements using HYPERMESH 14.0 and the joint are extracted. The present paper considers a total of 8 joint sections (i.e. A-pillar roof joint, A-pillar hinge joint, A-pillar rocker joint, B-pillar roof joint, B-pillar rocker joint, C-pillar roof joint, C-pillar rocker joint, D-pillar roof joint) and the required boundary conditions are applied to those joint sections. The joints are shown in figure 1.

The BIW is assumed to be conventional steel with elasticity modulus E=210GPa, density ϱ=7.8e-09 tonnes/mm^3, Poisson's ratio μ=0.3 and a thickness of t=1.25mm.

Fig. 1. BIW of a typical car



2.1 Boundary Condition

At the end sections of the joints, the nodes along the circumference are selected and RBE2 element is created. This is done at all the ends of the joint section so that loading condition can be applied at the end points of the joints. If one end of the joint

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is used to apply a force of 1N in X-direction, then the other ends of the joint are constrained in all 6 degrees of freedom (dof). This procedure is repeated by applying 1N force in Y and Z direction along all the end sections for all the joints. An example is shown in figure 2 and 3.

Fig. 2. 1N force along X-direction - A hinge

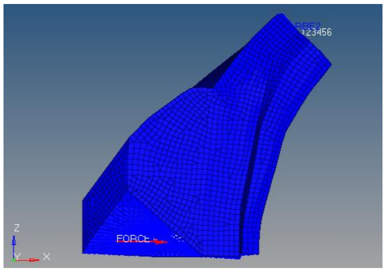
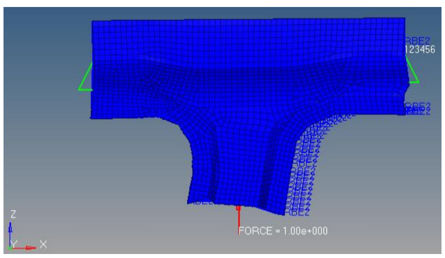


Fig. 3. 1N force along Z-direction – B roof



When the above mentioned method is adopted, there are a total of 19 different test cases after considering various end conditions. This is shown in table 1.

Table 1. Number of cases for all joints

Joint	No of cases
A pillar hinge joint	2
A pillar roof joint	2
A pillar rocker joint	2
B pillar roof joint	3
B pillar rocker joint	3
C pillar roof joint	3
C pillar rocker joint	2
D pillar roof joint	2
Total	19

2.2 Joint Stiffness Analysis

Joint stiffness analysis is performed to calculate the bending and torsional stiffness of the joints. JSA is an important criteria for the NVH performance of the vehicle.

Bending Stiffness – The displacement obtained by applying 1N load at the ends of the joints are substituted in the equation 1 to obtain the bending stiffness.

Bending Stiffness $K_b = \frac{F}{\delta}$ N/mm (1)

Torsional Stiffness - +/-1N load, representing a couple, is applied at the ends of the longest diagonal of the cut section along Y direction. All degrees of freedom (dof's) are fixed at the other ends of the joint. Y-axis displacement is obtained after running the simulation at the end points and termed as δ_1 and δ_2. They are approximately equal to each other ($\delta_1 \approx \delta_2$).

Torsional Stiffness $K_t = \frac{FL''}{\delta_1 \oplus \delta_2}$ N-mm/rad (2)

Where, F = Force applied in X, Y, Z directions, N
L = Normalized length of the longest diagonal of the cut section, mm
δ_i = Displacement, mm (i=1,2 – displacement at each end)

2.3 Modification of Critical Joints

Mobility curve or point mobility is a plot of displacement versus number of joint sections along the same line (along the length of the vehicle). The curve should more or less be a straight line. This indicates that the joints along a particular horizontal displace more or less equally maintaining stability or minimum distortion of the BIW structure. The phenomenon is also called match boxing in case of weaker joints where the BIW tend to twist or shear about the weak joint. To avoid this situation, by design, it is attempted to have same relatively displacements at each joint along the length of the vehicle. This is expected to ensure adequate stiffness and desired NVH behavior. Hence design modification is necessary for those joints which are critical (i.e. with high displacement). The joints that are critical are modified in two ways.

1. Increasing the thickness of the joint (geometry modification) - In the present paper, the critical joint thickness is increased from 1.25mm to 1.75mm. By doing so, the critical joints displacement is reduced and there is an increased bending and torsional stiffness.

2. Structural PU foam (material addition) - The use of PU foam in hollow BIW has become common in almost all cars. In the numerical method, the low density foam is filled inside the critical joints using 3D solid tetra elements. The foam properties used are Young's Modulus, E=2200MPa, Poisson's ratio = 0.35 and density 1.19E-9 tonnes/mm^3. The thickness is kept the same 1.25mm (original thickness).

The results are discussed below.

3 Results and Discussion

NX NASTRAN 9.0 is used to solve all the different cases considered to obtain the displacements for all the joints sections along X, Y and Z directions. The resulting displacement are tabulated and plotted to obtain point mobility curve.The displacements along X, Y and Z direction obtained from the analysis are shown in table 2. From these values, mobility curve is plotted accordingly in figures 4, 5 and 6 respectively.

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Table 2. Result for displacement

Joints	Cases	Displacement (mm)		
		Force along X-axis	Force along Y-axis	Force along Z-AXIS
A ROOF	1	2.14E-04	1.11E-03	6.38E-04
	2	3.62E-04	1.07E-03	5.94E-04
A HINGE	3	6.36E-05	3.83E-04	4.72E-05
	4	3.84E-04	8.62E-04	2.05E-04
A ROCKER	5	3.31E-05	1.88E-04	5.67E-05
	6	3.76E-05	2.19E-04	6.05E-05
B ROOF	7	8.09E-06	2.95E-04	1.31E-04
	8	9.95E-06	3.07E-04	1.11E-04
	9	6.35E-05	1.61E-03	7.44E-04
B ROCKER	10	4.73E-05	4.52E-04	1.03E-04
	11	4.17E-05	6.75E-04	1.49E-04
	12	3.24E-05	2.96E-04	7.15E-05
C ROOF	13	1.09E-05	1.68E-04	1.44E-04
	14	2.06E-05	3.28E-04	1.67E-04
	15	4.64E-05	2.15E-04	8.98E-05
C ROCKER	16	1.79E-04	7.43E-04	1.64E-04
	17	1.30E-04	4.39E-04	2.31E-04
D ROOF	18	1.92E-05	2.84E-04	7.63E-05
	19	1.21E-05	3.26E-04	4.38E-05

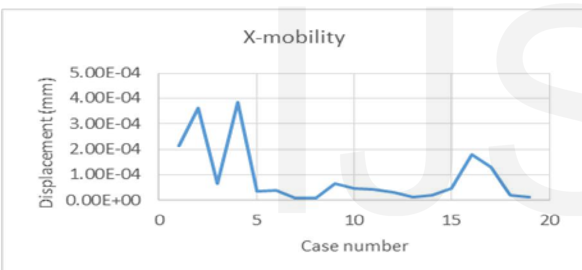

Figure 4: X-mobility curve shows high displacement in A-roof and A-hinge joint

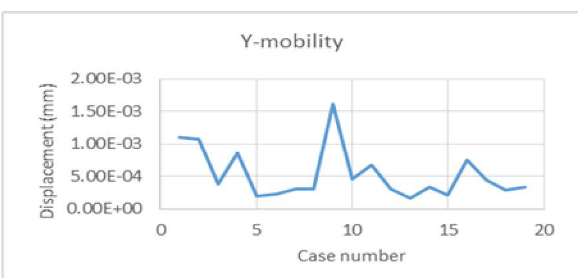

Figure 5: Y-mobility curve shows high displacement in B-roof joint

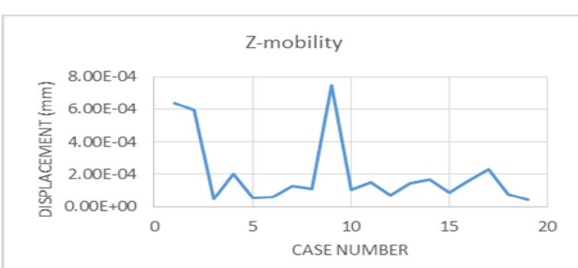

Figure 6: Z-mobility curve shows high displacement in A-roof and B-roof joint

Using the displacement values, the bending and torsional stiffness values are obtained for various joints using equations 1 and 2 in section 2.3. These are tabulated in table 3 and 4 below.

Table 3. Result for bending stiffness

Joints	Cases	Bending Stiffness (N/mm)		
		Along X	Along Y	Along Z
A ROOF	1	4666.36	901.71	1567.64
	2	2759.38	936.33	1683.79
A HINGE	3	15713.39	2612.33	21181.95
	4	2601.46	1160.36	4889.98
A ROCKER	5	30184.12	5316.32	17646.02
	6	26574.54	4566.21	16537.13
B ROOF	7	123639.96	3393.28	7662.84
	8	100542.93	3255.21	9033.42
	9	15757.96	623.05	1344.09
B ROCKER	10	21146.12	2212.88	9737.10
	11	23980.82	1482.58	6724.95
	12	30902.35	3374.96	13987.97
C ROOF	13	91827.36	5963.03	6930.01
	14	48496.61	3050.64	6006.01
	15	21537.80	4649.00	11133.38
C ROCKER	16	5595.97	1345.90	6086.43
	17	7722.01	2276.87	4329.00
D ROOF	18	52083.33	3521.13	13106.16
	19	82644.63	3067.48	22831.05

Table 4. Result for torsional stiffness

Joints	Cases	Displacement Along Y Axis (mm)	Length L (mm)	Torsional Stiffness (N-mm/rad)
A ROOF	1	4.55E-04	76.82	6.49E+06
	2	3.19E-04	63.75	6.37E+06
A HINGE	3	4.75E-05	70.18	5.18E+07
	4	2.01E-04	171.18	7.29E+07
A ROCKER	5	6.97E-05	206.80	3.07E+08
	6	9.73E-05	165.68	1.41E+08
B ROOF	7	1.42E-04	98.82	3.43E+07
	8	3.08E-04	99.01	1.59E+07
	9	3.42E-04	75.05	8.24E+06
B ROCKER	10	2.01E-04	162.80	6.61E+07
	11	2.12E-04	162.80	6.27E+07
	12	9.26E-05	213.50	2.46E+08
C ROOF	13	8.99E-05	132.36	9.74E+07
	14	1.60E-04	95.28	2.84E+07
	15	8.58E-05	170.68	1.70E+08
C ROCKER	16	5.58E-05	197.40	3.49E+08
	17	1.53E-04	161.20	8.52E+07
D ROOF	18	1.09E-04	133.55	8.18E+07
	19	9.88E-05	120.22	7.31E+07

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From the figures 4, 5 and 6, it is seen that there are 3 joints that have high displacements.

- A-roof for Case 1 and 2 when force is applied in X,Y,Z direction.
- A-hinge for Case 2 when force is applied in X direction.
- B-roof for Case 3 when force is applied in Y and Z direction.

So A-pillar roof, A-pillar hinge and B-pillar roof joint are critical joints that needs to be modified. Figures 7, 8 and 9 show the decrease in displacement for 1.75mm and 1.25mm with foam in comparison with 1.25mm without foam. It can also be seen that 1.25mm with foam performs better than 1.75mm thickness even though the difference is small. Hence both the methods give good results. However, another main criterion to look at is the specific stiffness property of joints.

Since change in the thickness and addition of foam inside the joint increases the mass, the stiffness per unit mass or specific stiffness is calculated. By doing this, mass penalty is taken into account. Tables 5 and 6 show the percentage increase in the specific stiffness properties.

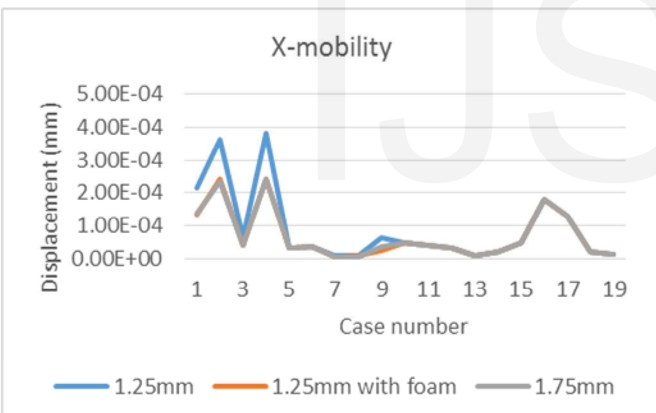

Fig. 7. Comparison of X-mobility curve

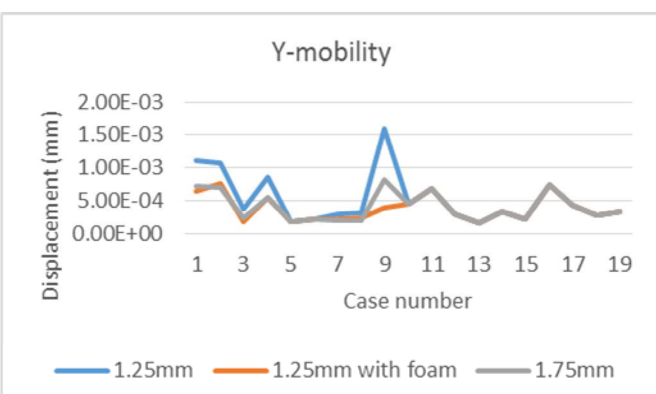

Fig. 8. Comparison of Y-mobility curve

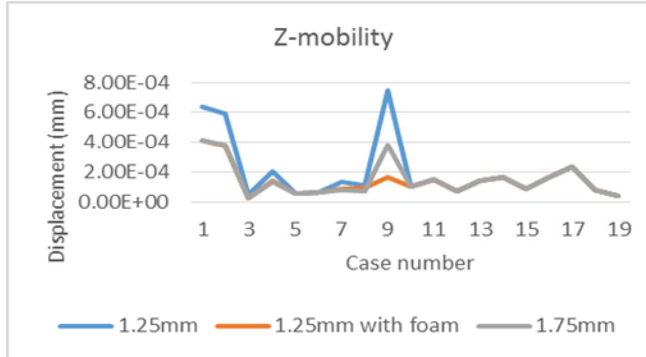

Fig. 8. Comparison of Y-mobility curve

Table 5. Percentage increase in Specific Stiffness of 1.75mm shell thickness from 1.25mm shell thickness without foam

Joints	Cases	Percentage Increase In Bending Stiffness/Unit Mass(N/mm/kg)			Percentage Increase In Torsional Stiffness Per Unit Mass (N-mm/rad/kg)
		X	Y	Z	
A ROOF	1	9.49	10.65	10.38	12.59
	2	10.57	8.62	10.50	17.42
A HINGE	3	16.14	17.90	16.33	8.32
	4	13.07	12.81	11.17	25.79
B ROOF	7	11.36	4.67	12.85	7.65
	8	9.03	5.07	4.85	118.78
	9	26.89	38.93	39.63	28.86

Table 6. Percentage increase in Specific Stiffness of 1.25mm with foam from 1.25mm without foam.

Joints	Cases	Percentage Increase In Bending Stiffness/Unit Mass(N/mm/kg)			Percentage Increase In Torsional Stiffness Per Unit Mass (N-mm/rad/kg)
		X	Y	Z	
A ROOF	1	41.51	52.34	36.82	113.33
	2	32.06	25.09	39.12	117.42
A HINGE	3	35.74	81.57	46.86	10.04
	4	41.19	38.69	31.33	90.27
B ROOF	7	40.44	18.63	30.47	55.61
	8	28.22	22.31	10.68	201.10
	9	142.65	271.60	303.89	596.49

With an initial thickness of the BIW of 1.25mm, the mobility map plotted had high peaks at certain crucial joints. These had to be modified for better NVH performance. From the figures 7, 8, 9 and tables 5, 6 of comparison, it is clear that 1.25mm shell thickness with foam performs better in every aspect compared to 1.75mm shell thickness without foam. The displacement of 1.25mm with foam and 1.75mm shell thickness isclose to each other but the major difference between them is seen in the stiffness properties. The specific stiffness of 1.25mm with foam clearly better than the 1.75mm shell thickness. This is attributed to the increase in mass of nearly 40-45% in 1.75mm whereas in 1.25mm with foam there is mass increase of just 10-12%. This results in lesser weight penalty with improved NVH characteristics.

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4 Conclusion

A systematic study of the critical joints of a typical BIW of a car is presented in this paper. It is evident that the use of structural foam inside the BIW improves joint stiffness and point mobility. This is also expected to improve the overall NVH behavior of the vehicle As such over the last decade, the use of foams inside the car body is increasing and research is going on to further improve the overall performance of the car.

On the contrary, the body cannot be made very stiff because the car may qualify with enhanced NVH performance but may fail in crash test. Having more stiffness although good for NVH is not necessarily good for a crash phenomenon. This is because more stiff would mean more force on to the occupant. This may not be necessarily safe under crash situations, a strength dependent phenomenon. Hence a typical vehicle is a compromise between NVH and safety. Automotive design and engineering therefore subjects itself to continuing research.

The present paper is limited to use of only steel as the body material, but there are many other materials that can be used such as aluminium and composites. They give a good competition to the steel auto-body makers in the market. Further study can be made as to which material exhibits the best overall performance. This includes cost consideration, fuel economy, NVH and stiffness properties.

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