10. Testing and Results

10. Testing and Results

10.1. Scope of Work

To prove the structural integrity of the ULSAB demonstration hardware, the following test procedures were executed as part of the ULSAB program in Phase 2.

- Static rigidity
  - Static torsion
  - Static bending

- Modal analysis
  - 1st Torsion mode
  - 1st Bending mode
  - 1st Front end lateral mode

- Mass
  - DH mass in test configuration

All testing work was performed at Porsche's R & D Center in Weissach.

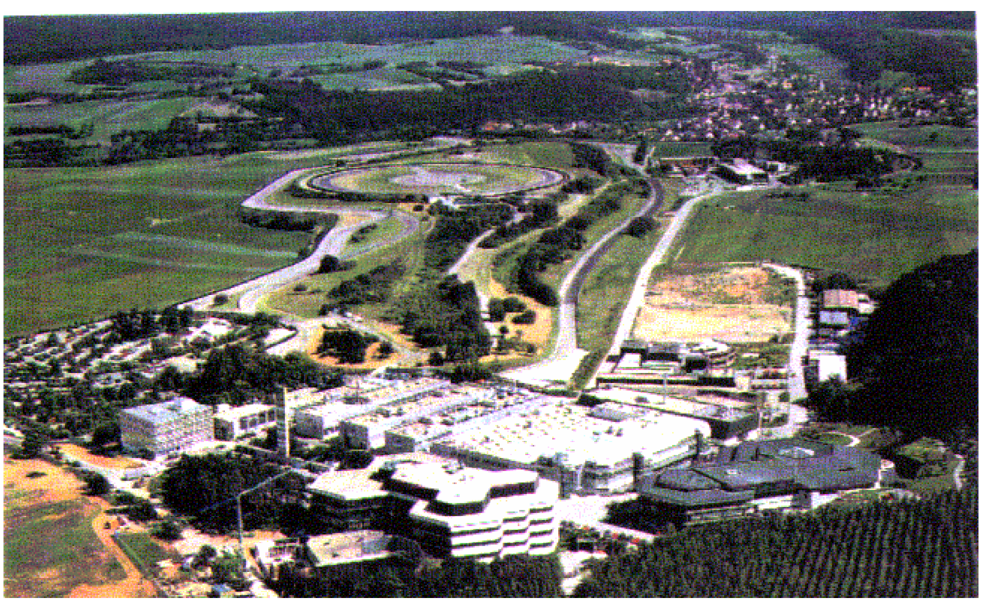

Fig 10.1-1 Aerial View

10.2. Targets

The main factors affecting the ride and handling of the vehicle are Noise, Vibration and Harshness, known as NVH behavior. To achieve the desired levels of comfort for the occupants, the vehicle body must have high static and dynamic rigidity. In other words, the auto body should have high stiffness. This is required because the increased rigidity improves the vehicle resistance to excitement caused by the drive train, the engine or by road conditions such as bumps and potholes. When excited, the car body vibrates at particular frequencies, called its natural frequencies, and also in a particular manner called its mode shape. The mode shapes are for instance on: global torsion mode, global bending mode and front end lateral mode.

Another result of good rigidity would be minimal deviations in the dimensions of the body structure openings such as the hood, front door, rear door and deck lid under load conditions. These movements between the body structure and the closure panels often create sounds.

Furthermore, it should be proven that the received numbers from the analysis by FE-calculations are in correlation with the results gathered by the testing procedure.

Based on the current average of selected, benchmarked vehicles in Phase 1, the following targets for the ULSAB structure were established:

Performance	Targets
Mass	$\leq$ 200 kg
Static torsional rigidity	$\geq$13,000 Nm/deg
Static bending rigidity	$\geq$12,200 N/mm
First body structure mode	$\geq$ 40 Hz

NOTE: Structural performance with windshield and backlight; mass without windshield and backlight.

10.3. Static Rigidity

10.3.1. Test Setup

10.3.1.1. General

The DH in full test configuration consists of the following parts:

- Welded Body Structure
- Bonded Windshield and Back Light
- Bonded and bolted Panel Dash Insert (Part-No. 022)
- Bonded Panel Spare Tire Tub (Part-No. 050)
- Bolted Reinforcement Panel Dash Brake Booster (Part-No. 115)
- Bolted Braces Radiator (Part-No. 188)
- Bolted Reinforcement Radiator Rail Closeout RH/LH (Part -No. 094/095)
- Bolted Reinforcement Radiator Support Upper (Part-No. 001)
- Bolted Tunnel Bridge Lower/Upper
- Bolted Brace Cowl to Shock Tower Assembly

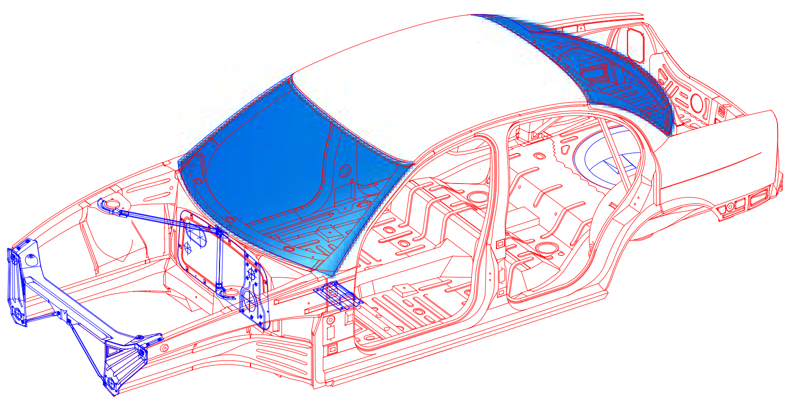

Figure 10.3.1.1-1 DH with Bonded / Bolted Parts

The unpainted body structure was measured without front and rear suspension system. The body structure was held at four points: the front; at Panel Skirt RH/LH (Part-No. 096/097) and the rear; at Plate Rear Spring Upper (Part-No. 110).

Along the front rails, the rockers, and the rear rails 12 stadia rods were attached. Twenty-four electronic feelers measured the movements of these rods.

Aluminum panels with glass thickness were used to simulate the bonded windshield and backlight. Due to the fact that the related material property for rigidity and stiffness, the Youngs modulus, shows a close similarity for glass and aluminum. This can be done without compromising the test results, but taking advantages in timing and cost.

10.3.1.2. Static Torsion

The DH was mounted to the test rig with rigid tubes. Two rear locations at the plate spring rear upper were constrained, while the load was applied to panel skirt RH/LH by a scale beam.

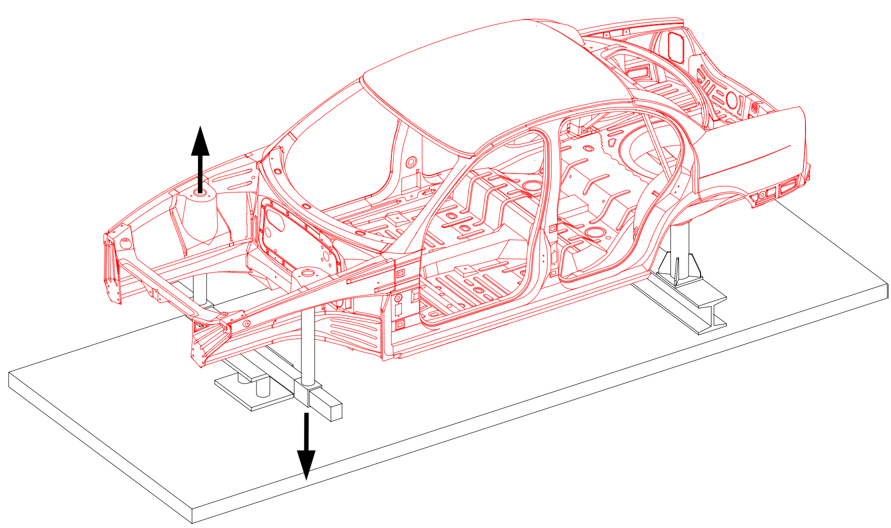

Figure 10.3.1.2-1 Test Configuration for Static Torsion

The measurements were taken with four different loads from M_t=1000Nm to $M_t$max=4000Nm.

Before starting the measuring procedure, the maximum load was applied to the DH to eliminate the sag rate.

10.3.1.3. Static Bending

The DH was mounted to the test rig by rigid tubes. The four fixing points of the DH were constrained.

The loads were applied to the center of the front seats and to the center of the two outer rear seats.

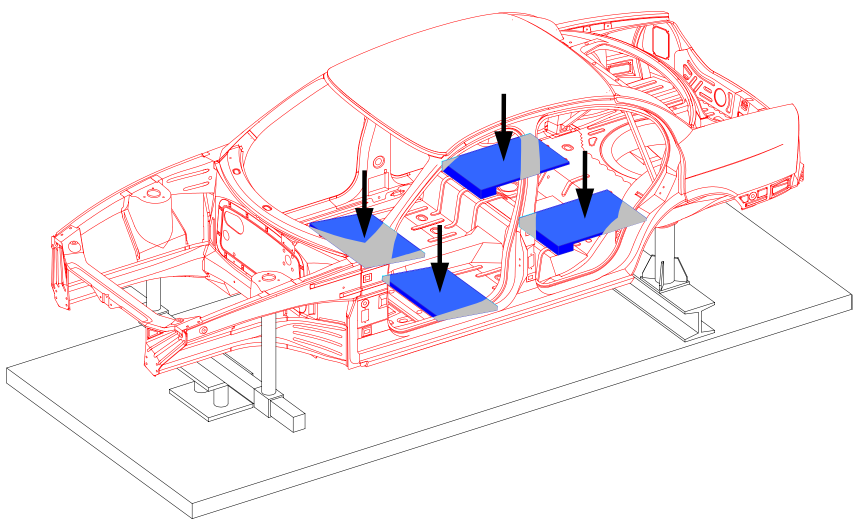

Figure 10.3.1.3-1 Test Configuration for Static Bending

The measurements were taken with four different loads from F_b = 1000 N (4 x 250 N) to $F_b$max = 4000 N (4 x 1000 N).

Before starting the measuring procedure, the maximum load was applied to the DH to eliminate the sag rate.

10.3.2. Results

10.3.2.1. Static Torsion

Figure 10.3.2.1-1 DH on Test Rig for Static Torsion

The torsional rigidity for the test unit in the configuration described in section 10.3.1.1 is:

With glass	21,620 Nm/deg
Without glass	15,790 Nm/deg

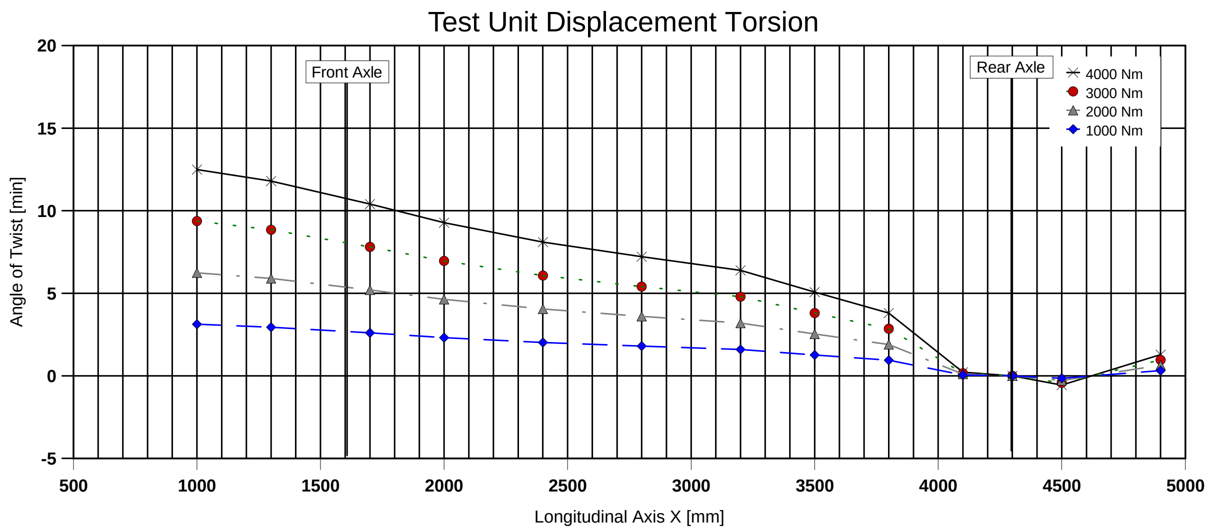

Figure 10.3.2.1-2 Torsion Lines 4 Load Cases with Glass

In general, the graph plot is running harmonic. There is only a jump in rigidity between x = 3800 to x = 4200. This is related to the positive impact of the Member Pass Through (Part-No. 090) to the torsional stiffness.

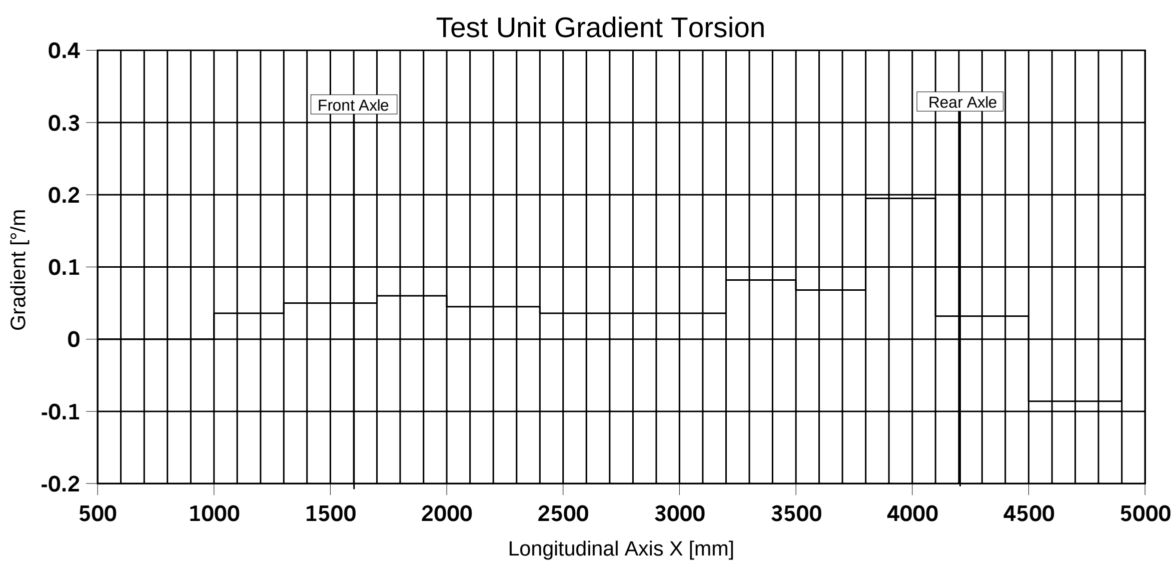

Figure 10.3.2.1-3 Gradient of Torsion Line with Glass

The above graph shows the gradient of the torsion line. The disharmonies of the torsion line can be seen in a higher resolution.

The torsional rigidity for DH #2 in the configuration described in section 10.3.1.1 is:

With glass	20,800 Nm/deg
Without glass	15,830 Nm/deg

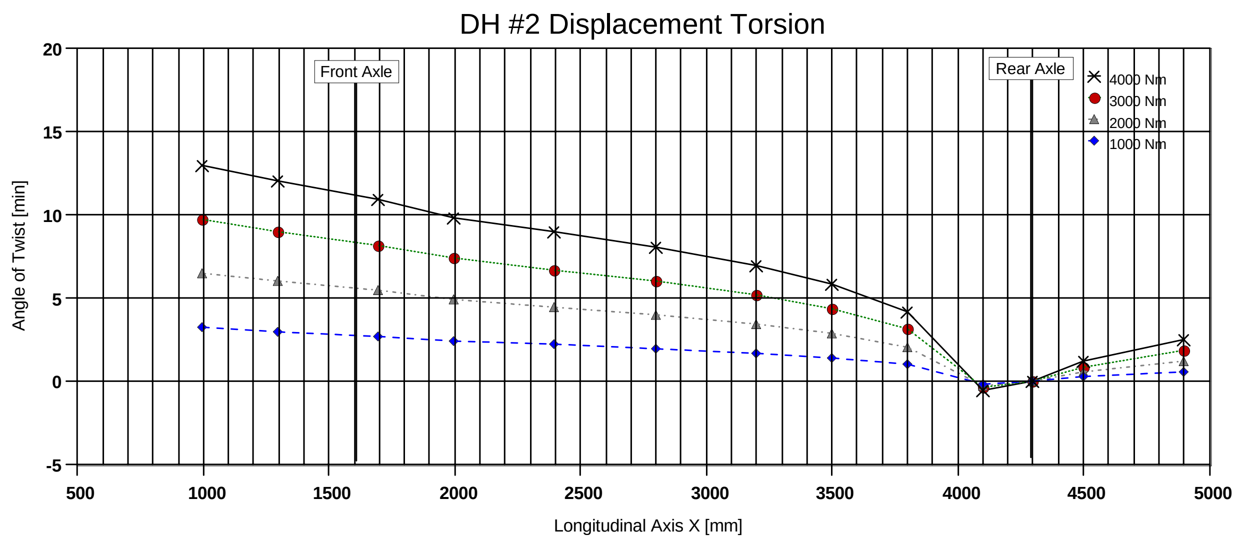

Figure 10.3.2.1-4 Torsion Lines 4 Load Cases with Glass

As expected, the results are very close to the test unit.

This assumption is based on the test results without glass, because these are nearly identical (15,790 Nm/deg vs. 15,830 Nm/deg).

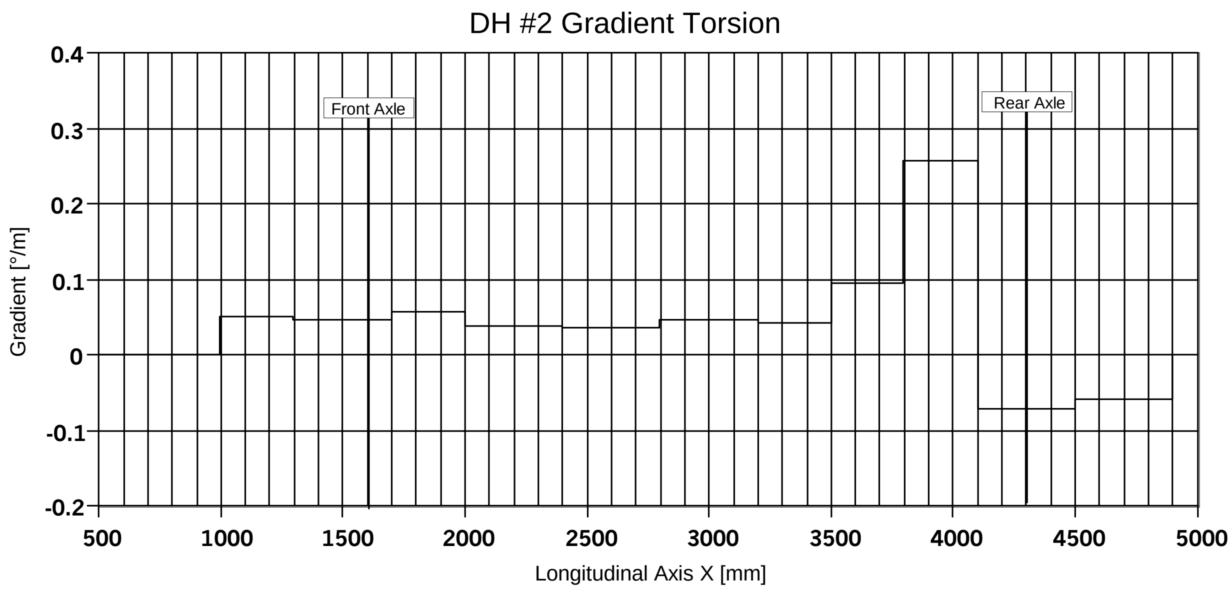

Figure 10.3.2.1-5 Gradient of Torsion Line with Glass

The above graph shows the gradient of the torsion line. The disharmonies of the torsion line can be seen in a higher resolution.

To investigate the impact of several bonded and/or bolted parts, additional measurements in various test configurations were undertaken with the test unit.

Test Configurations:

1. Full configuration as described in Section 10.3.1.1
2. As 1, but without braces radiator (Part-No. 188)
3. As 2, but without radiator support upper (Part-No. 001/094/095)
4. As 3, but without bolted brace cowl to shock tower assembly
5. As 4, but without tunnel bridge

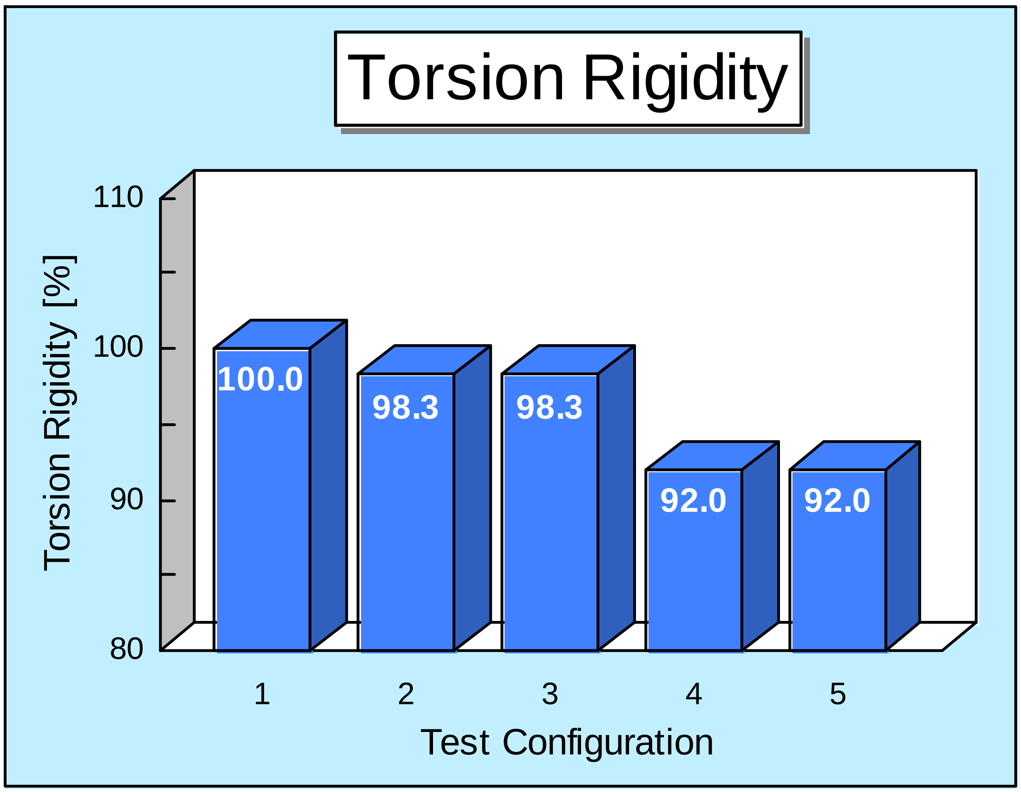

Figure 10.3.2.1-6 Torsion Rigidity Five Test Configurations

As the numbers show, only the bolted brace cowl to shock tower assembly has a significant impact on the torsional rigidity of 6.3%.

10.3.2.2. Static Bending

Figure 10.3.2.2-1 DH on Test Rig for Static Bending

The bending rigidity of the test unit in the configuration described in Section 10.3.1.1 is:

With glass	20,460 N/mm
Without glass	17,150 N/mm

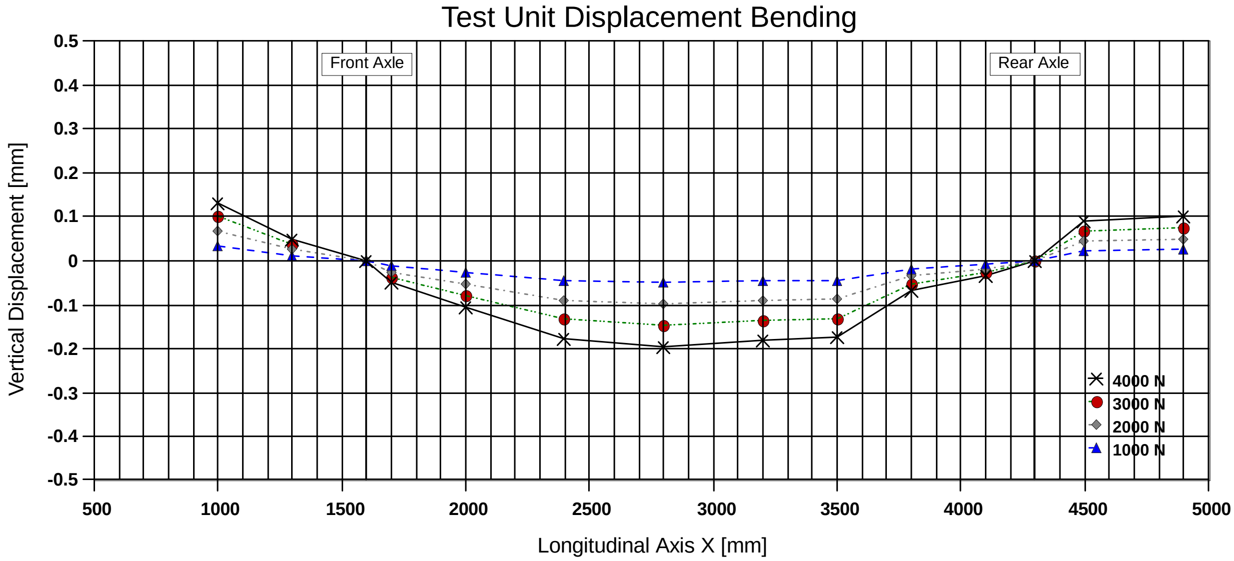

Figure 10.3.2.2-2 Bending Lines 4 Load Cases with Glass

The graph is running harmonic. There is only a local increase in bending rigidity between x = 3500 and x = 4200. This indicates a stiff joint between rocker and rear rails. Furthermore, Porsche relates this to the design of the side roof rail.

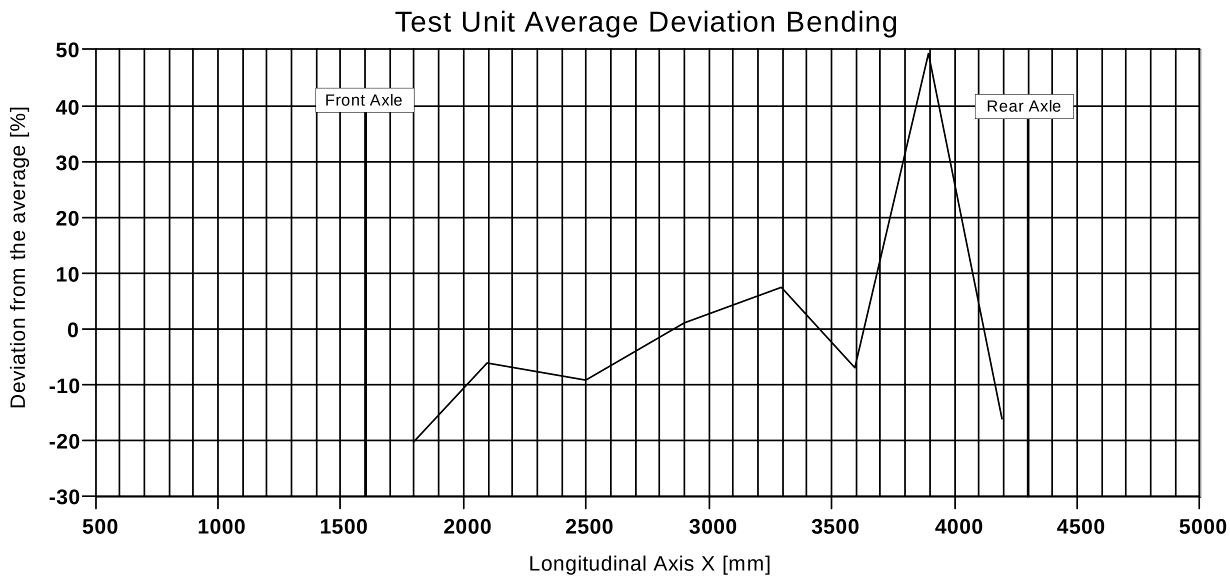

Figure 10.3.2.2-3 Deviation from the Average Bending Line with Glass

The above graph shows the deviation from the average value of the bending line. The disharmonies can be seen in a better resolution.

The bending rigidity for DH #2 in the configuration described in Section 10.3.1.1 is:

With glass	18,100 N/mm
Without glass	15,950 N/mm

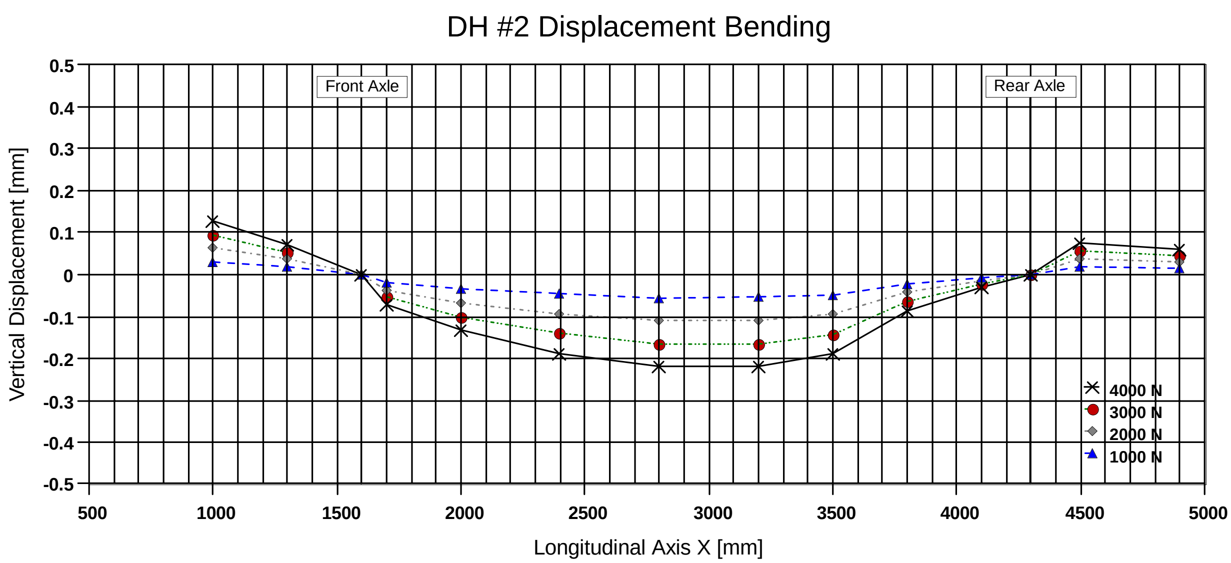

Figure 10.3.2.2-4 Bending Lines 4 Load Cases with Glass

The bending lines show the same characteristics as for the test unit, but the absolute value decreased by 11%. The local increase between x=3500 and x=4200 is not so evident as it was on the test unit. This could be created by local modifications of the side roof rail and the rear rails for improved manufacturing. Furthermore, the material gage of the panel roof changed from 0.77mm to 0.70mm due to material availability problems for the test unit; this was also a factor for the decrease of the absolute value.

Additionally Porsche has experienced that static rigidities of body structures differ by plus/minus five percent (5%) even under series production conditions.

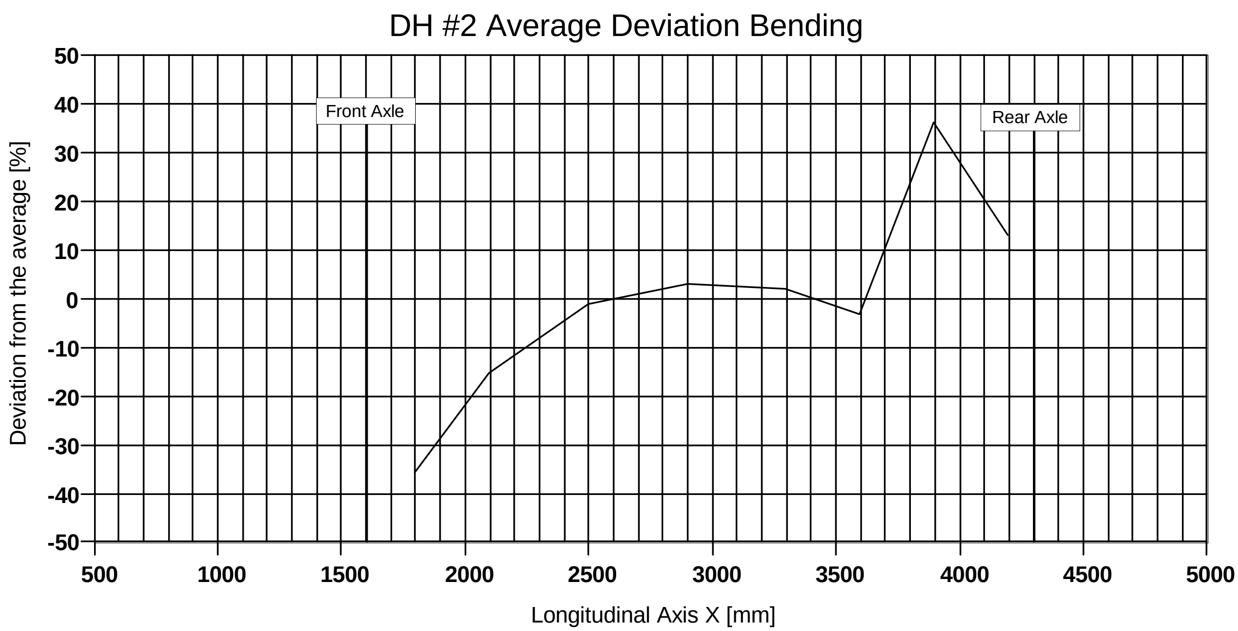

Figure 10.3.2.2-5 Deviation from the Average Bending Line with Glass

The above graph shows the deviation from the average value of the bending line. The disharmonies can be seen in a better resolution.

To investigate the impact of several bonded and/or bolted parts, additional measurements were undertaken:

Test Configurations:

1. Full configuration as described in Chapter 10.3.1.1
2. As 1, but without braces radiator (Part-No. 188)
3. As 2, but without radiator support upper (Part-No. 001/094/095)
4. As 3, but without bolted brace cowl to shock tower assembly
5. As 4, but without tunnel bridge

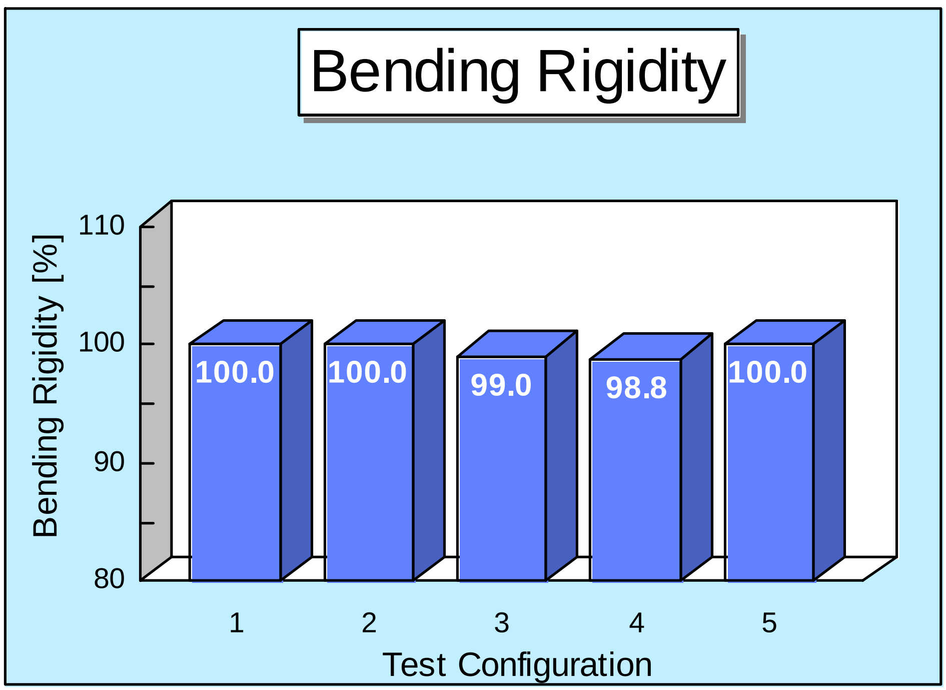

Figure 10.3.2.2-6 Bending Rigidity Five Test Configurations

As the numbers show, none of these parts display a significant impact on bending rigidity.

The increase from test configuration four (4) to test configuration five (5) is caused by local effects of the tunnel bridge to the displacement of the rocker. This behavior was also noticed in other body structures.

10.4. Modal Analysis

10.4.1. Test Setup

A modal analysis describes the vibration behavior of a structure. Results of a modal analysis are the resonance frequencies of the specific structure and the corresponding mode shapes (how the structure vibrates).

The ULSAB structure was suspended on a test rack held by rubber straps to decouple the test unit from the supporting structure of the test rack.

In order to find the mode shapes and the resonance frequencies, energy is applied to the structure. The response of the structure (in general the acceleration at different points) is measured in relation to the input forces. From the contribution of each input force to each response value, the dynamic behavior of the structure is calculated.

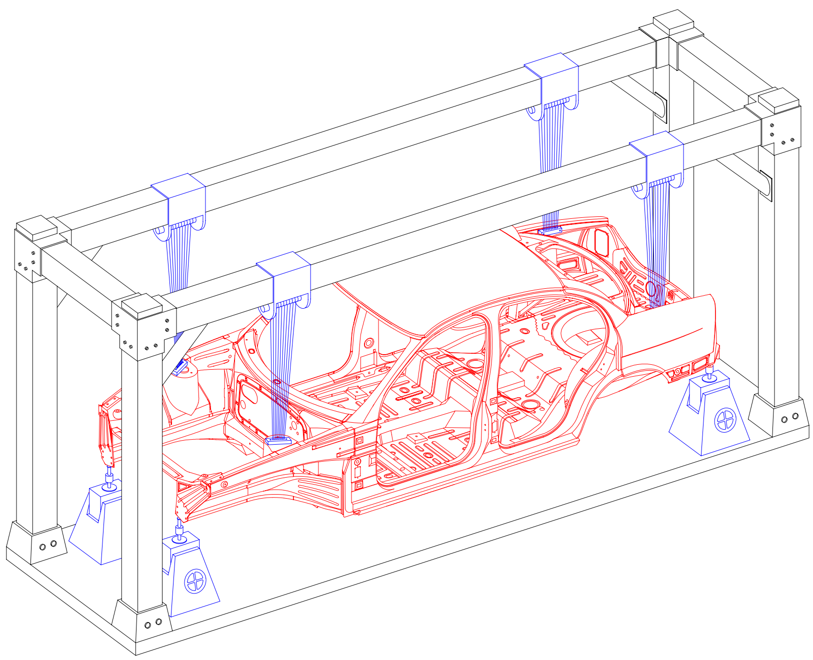

Figure 10.4.1-1 Test Configuration for Modal Analysis

In the case of the ULSAB, the body structure is excited by means of four electrodynamic shakers that are coupled to the corner points of the structure.

The simultaneous excitation with four shakers is necessary to provide good energy distribution into the structure and to minimize the influence of possible nonlinearities to the quality on the results. In addition, the torsion and bending modes of the body can be excited definitely. Torsion and bending are the most important global modes of a body structure.

Each of the four shakers is driven by a computer-generated, statistical independent band limited (0 to 100 Hz) Gaussian random noise spectrum. The response of the structure is determined by measuring vibration transfer functions between the acceleration at each measurement point in three orthogonal directions and each driving force.

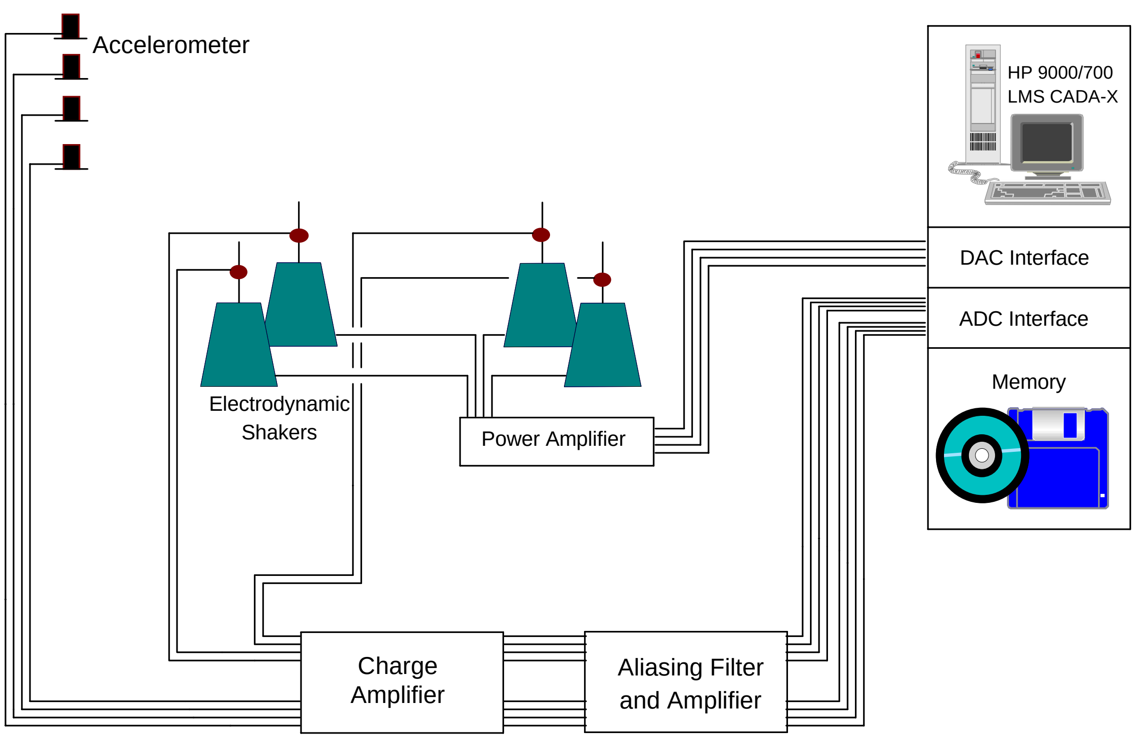

Figure 10.4.1-2 Set-Up for Modal Analysis

The global parameters of the structure, frequency and damping are determined thereafter by a Least Squares Complex Exponential (LSCE) fitting.

The modal displacement is calculated subsequently by fitting a Multiple Degree of Freedom (MDOF) model to the transfer functions in the time domain.

The test configuration of the test unit was exactly the same as the testing of static rigidities described in section 10.3.1.1.

10.4.2. Results

Figure 10.4.2-1 DH on Test Rig for Modal Analysis

The global modes of the test unit in the described test configuration can be seen in the following chart:

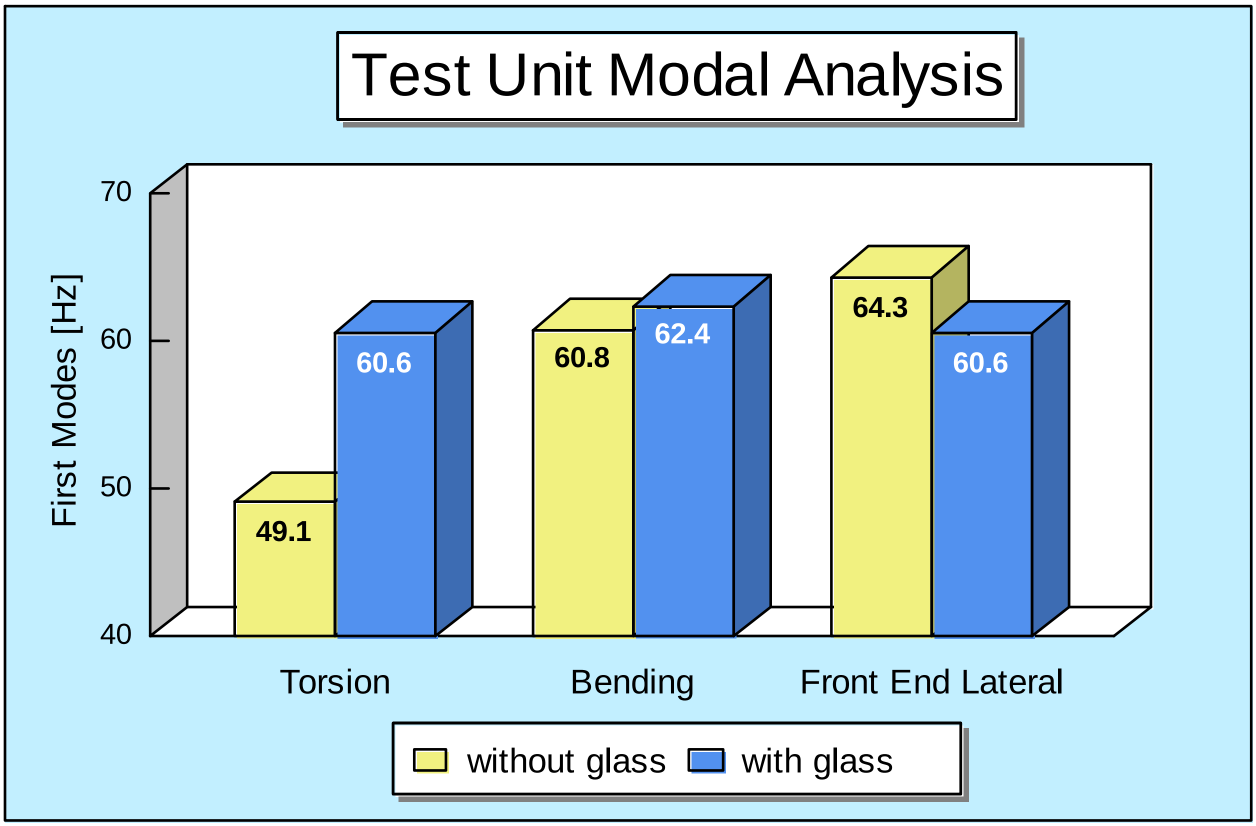

Figure 10.4.2-2 Modal Analysis Results - Test Unit

The dynamic rigidity of the ULSAB structure is remarkably good, as it was already indicated by the static test results. Windshield and backlight have a significant impact on the first torsion mode. The difference is in the same range, as known from other sedan body structures.

The effect on first bending and first front-end lateral mode is relatively small. For the test configuration with glass, the first torsion mode and the first front-end lateral mode are coupled at 60.6 Hz.

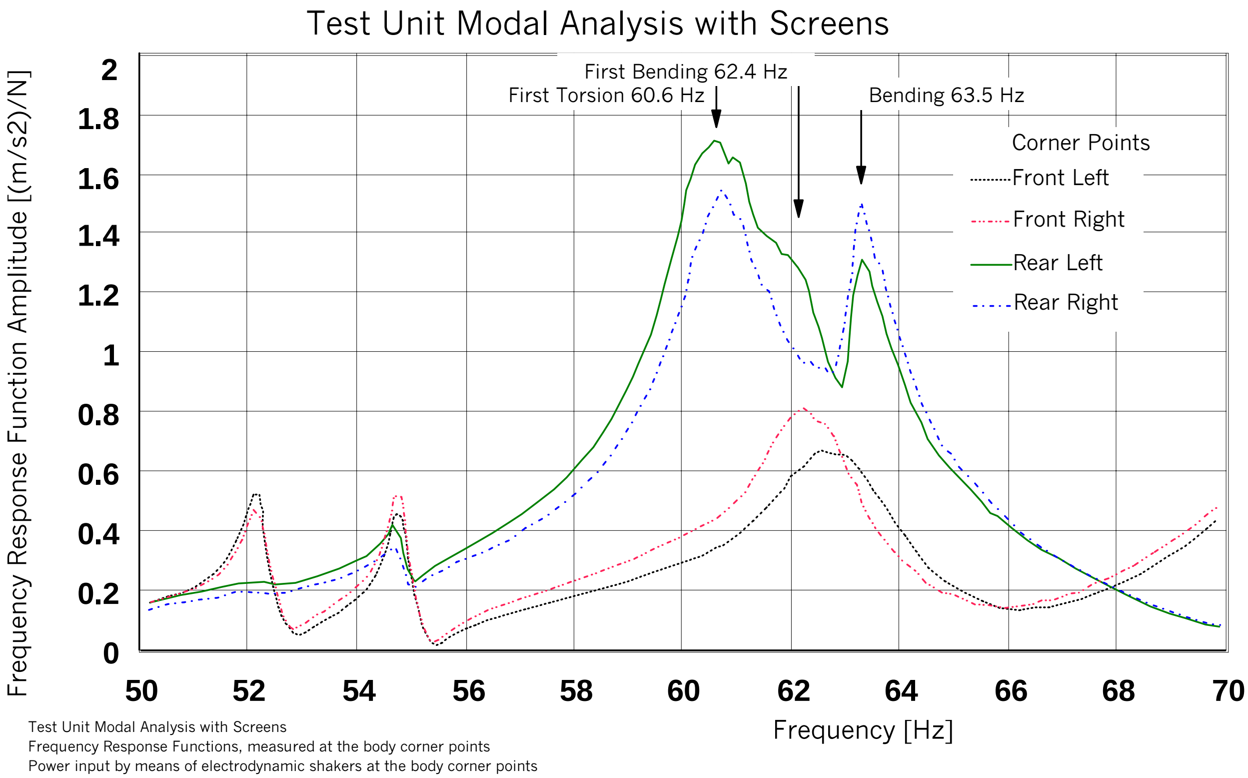

Figure 10.4.2-3 Frequency Response Functions - Test Unit

The graph plot above shows the frequency response functions, measured at the four driving points. Second bending mode at 63.5 Hz occurs mainly in the rear; whereas the first bending mode occurs in the front and rear of the structure.

The global modes for DH #2 in the described test configuration can be seen in the following chart:

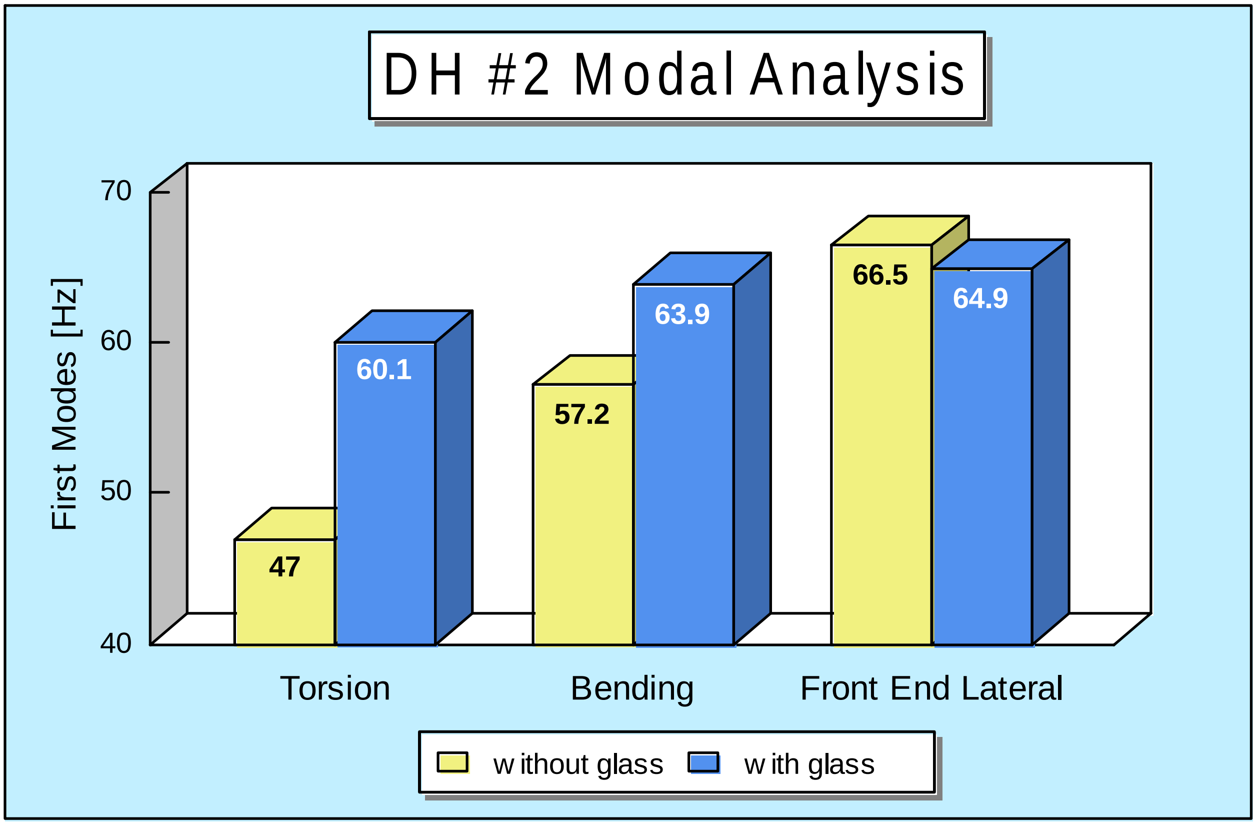

Figure 10.4.2-4 Modal Analysis Results - DH #2

The dynamic rigidity of DH #2 is in the same range as the values of the test unit. The front-end lateral mode changed remarkably. This is created by the change of the material gauge of the rail fender support inner from 0.9mm to 1.2mm.

The torsion mode and bending mode without glass decreased slightly, but with glass, the loss of dynamic rigidity is compensated.

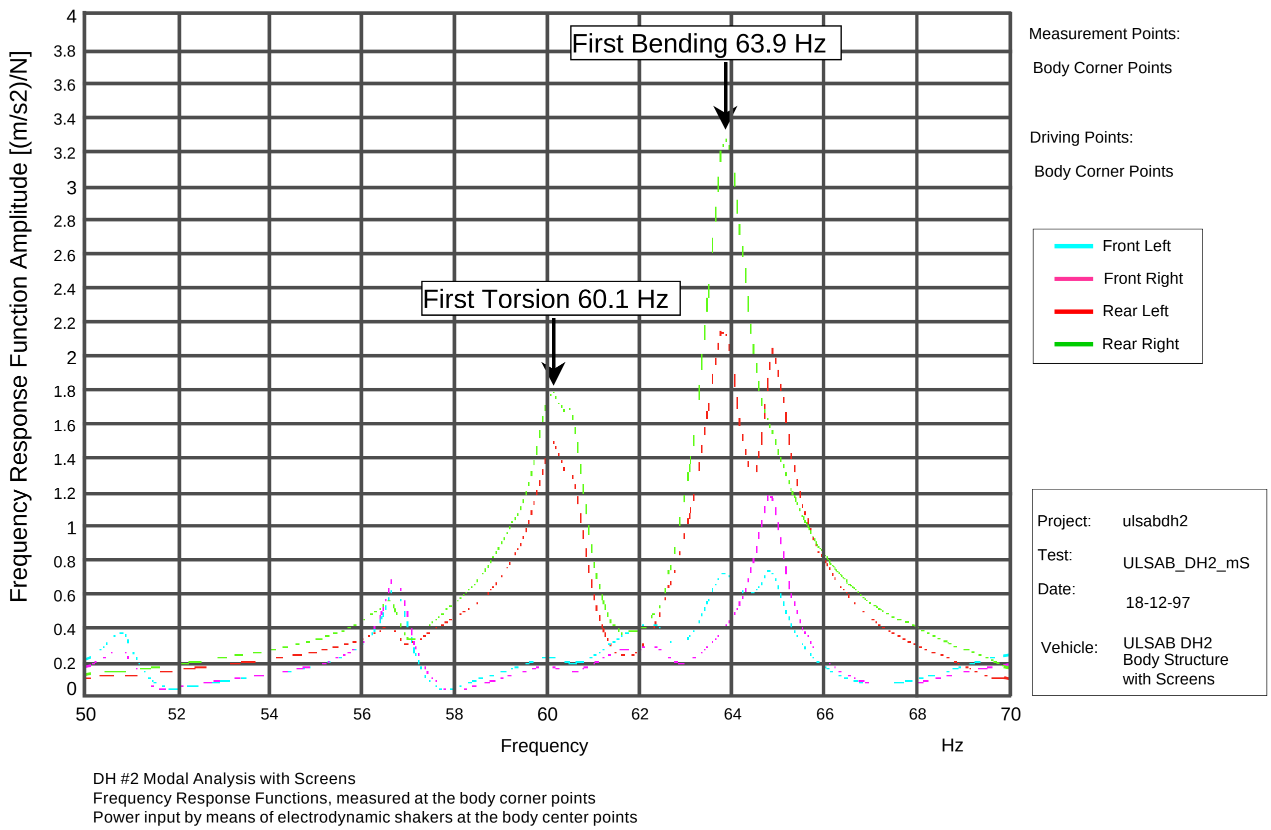

Figure 10.4.2-5 Frequency Response Functions - DH #2

The graph plot above shows the frequency response function, measured at the four driving points. The amplitude of the first bending increased in relation to the test unit. This is in correlation with the decrease of the static bending rigidity.

Additional modal analysis was conducted on the ULSAB structure, to investigate the influence of several bolted and/or bonded parts.

Test configurations:

1. Full test configuration as described in chapter 10.3.1.1.
2. As 1, but without bolted brace cowl to shock tower assembly
3. As 2, but without braces radiator (Part-No.188)
4. As 3, but without tunnel bridge
5. As 4, but without radiator support upper (Part-No. 001/094/095)

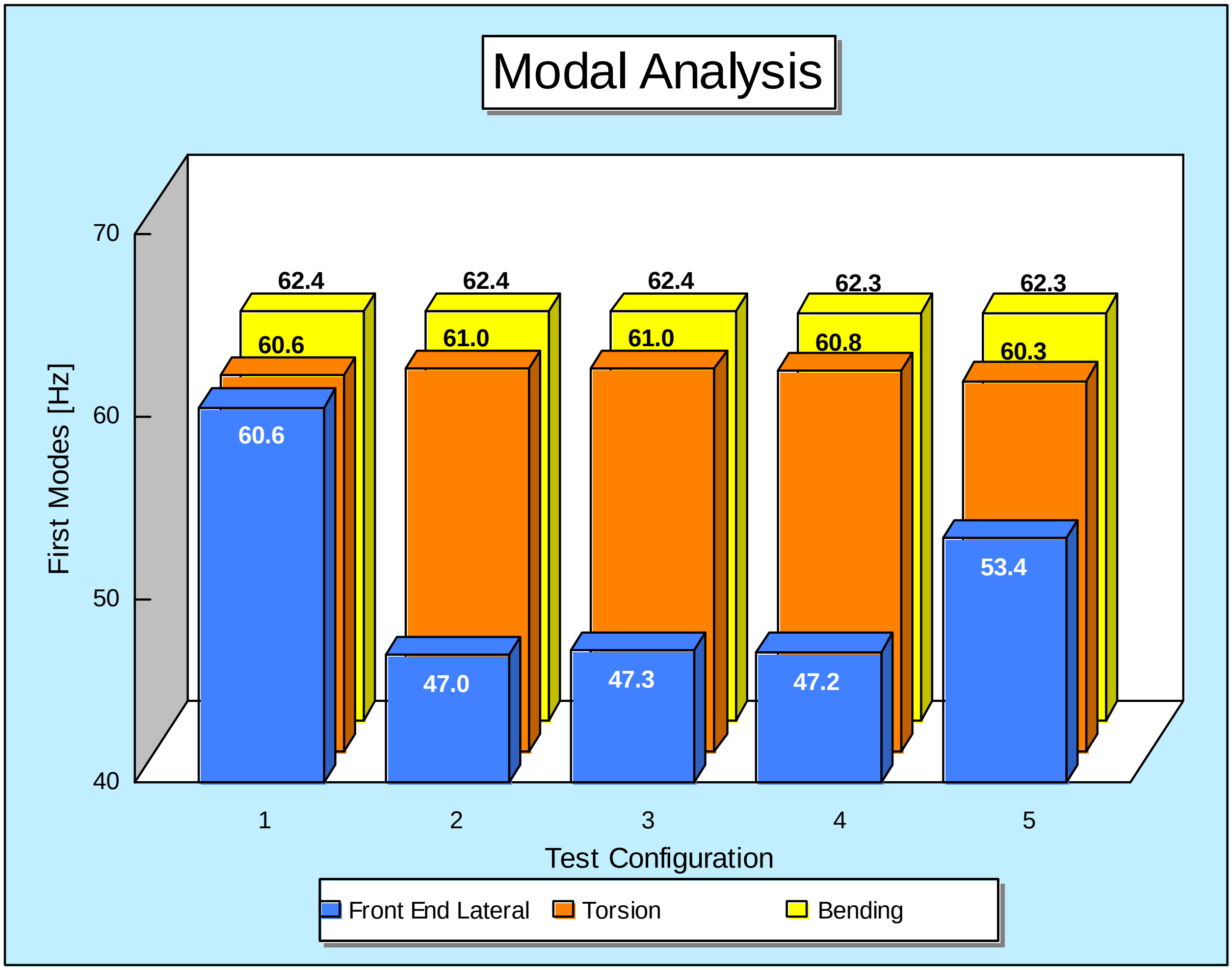

Figure 10.4.2-6 Modal Analysis Five Test Configurations

The influence of the bolted brace cowl to shock tower assembly on the front-end lateral mode of 13.6 Hz is evident.

Test configuration 5 shows an improvement in the front-end lateral mode, but this is mainly caused by the influence of the mass of assembly radiator support.

The other modifications have no evident impact on dynamic rigidity.

10.5. Masses in Test Configuration

A crane with a scaled load cell balanced the DH.

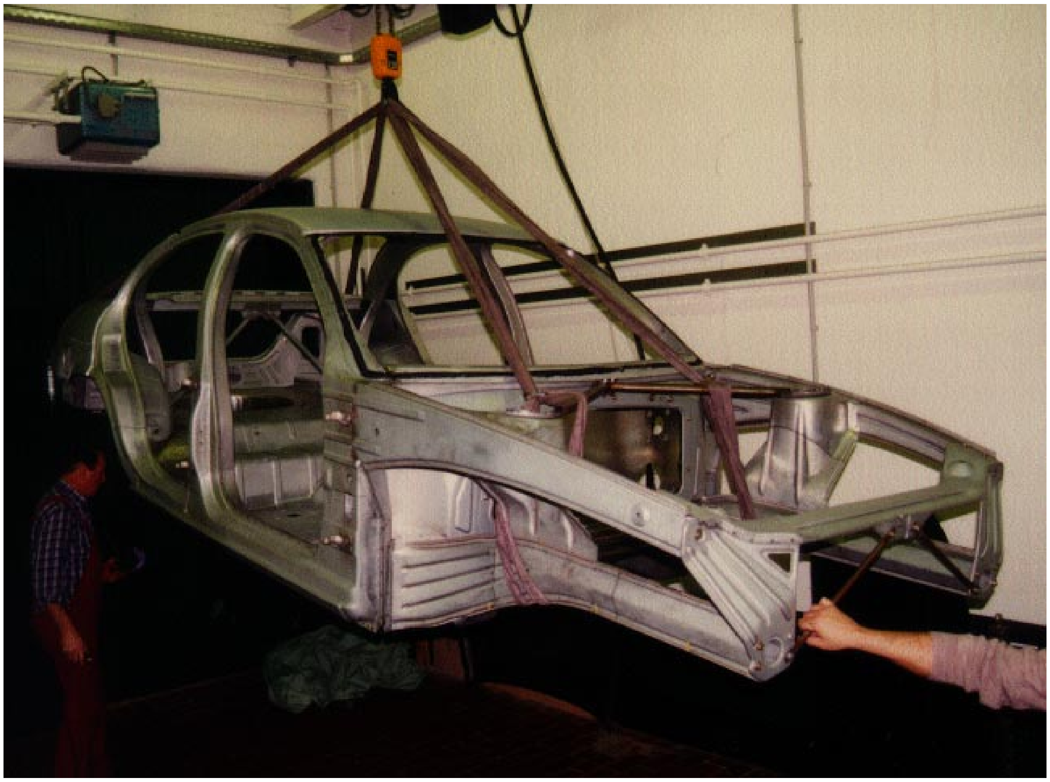

Figure 10.5-1 DH #2 on Crane

The measured mass in full test configuration included the mass of the bolted brace cowl to shock tower assembly and tunnel bridge, which were installed for testing only (see 10.3.1.1 Test Configurations). The mass of Windshield and backlight were not included. The mass in this test configuration was the following:

Test Unit	197.3 kg
DH #2	198.5 kg

**This mass includes 2.86 kg for the bolted brace cowl to shock tower assembly and tunnel bridge*

The calculated mass for non-constructed reinforcements and brackets has to be added (see Chapter 5 on Design and Engineering).

10.6. Summary

All test results proved excellent performance and coordination between test results and CAE results for structural performance values.

This is caused by the fact that the approach from former times, to define the structural body parts by these requirements, is superseded. Nowadays, these body parts are mainly specified by safety requirements.

ULSAB Testing Results Overview vs. CAE Results

Testing	Testing		CAE		Benchmark Average	Targets
	DH #2	Test Unit	Final Version	Test Unit		
Static Rigidity						
Torsion (Nm/deg)	20,800	21,620	20,350	19,020	11,531	≥ 13,000
Bending (N/mm)	18,100	20,460	20,540	20,410	11,902	≥ 12,200
Modal Analysis						
Torsion (Hz)	60.1	60.6	61.4	61.1	38*	≥ 40
Bending (Hz)	63.9	62.4	61.8	64.1	38*	≥ 40
Front End Lateral (Hz)	64.9	60.6	60.3	58.5	38*	≥ 40

**1st mode shape varied for each vehicle benchmarked*

The results gained by CAE calculations are in good, if not excellent, correlation with the test results.