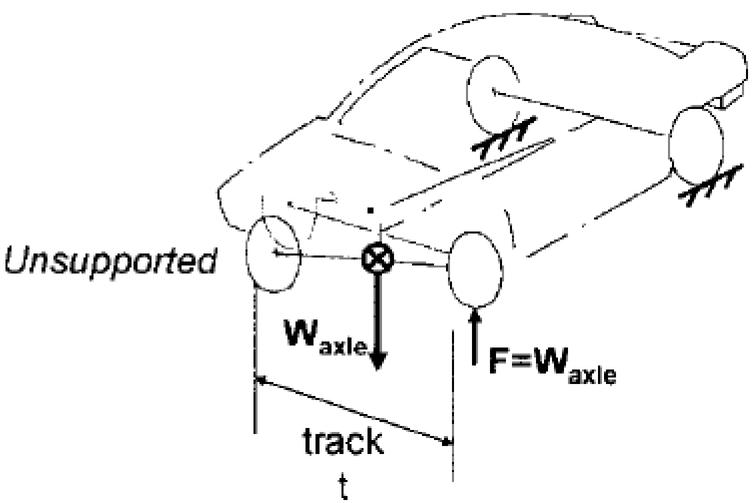
Design for Body Torsion

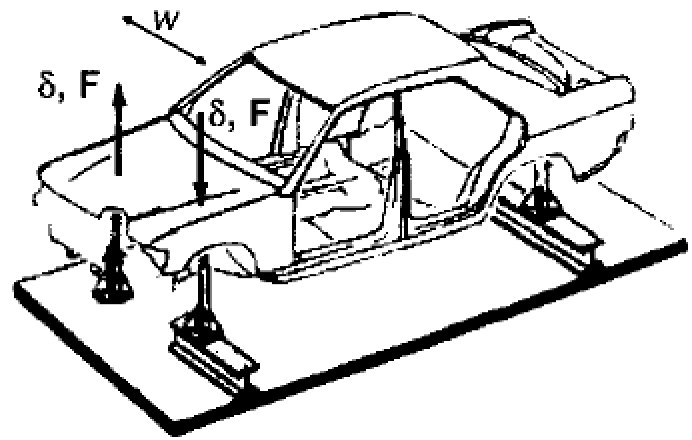
- Body torsion requirements
  - Body torsion strength
  - Body torsion stiffness
  - For midsize vehicle: K = 12000 Nm/°, T = 6250 Nm
- Internal loads during global torsion: load path analysis
- Analysis of body torsional stiffness
  - Shear strain energy
  - Effective shear stiffness
- Torsional stiffness of convertibles and framed vehicles

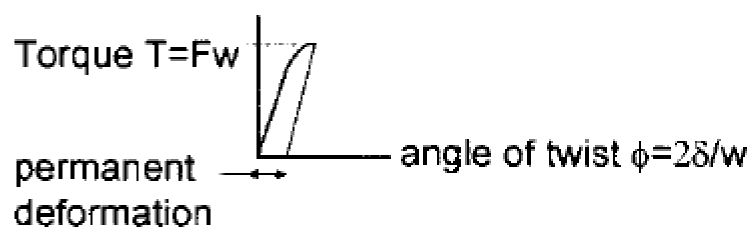
5.1 Body Torsion Strength Requirement

- Maximum torque to recover its shape with little deformation upon removal
- Vehicle-use condition: twist ditch maneuver
  - Input: δ, output: F (load cell)



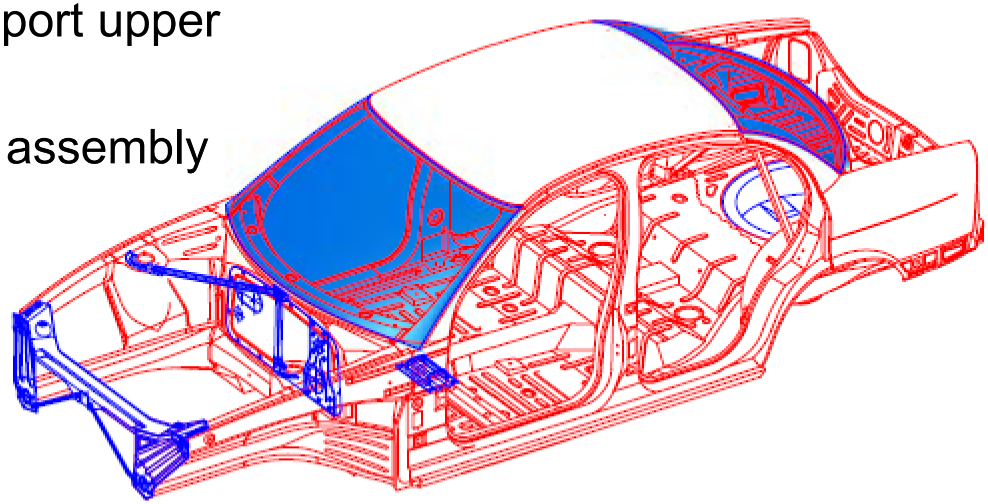
$$T_{\max} = W_{axle} \frac{t}{2}$$





Test Configuration

- Welded body structure
- Bonded windshield and back light (aluminum panels)
- Bonded and bolted panel dash insert
- Bonded panel spare tire tub
- Bolted reinforcement panel dash brake booster
- Bolted braces radiator
- Bolted reinforcement radiator rail closeout RH/LH
- Bolted reinforcement radiator support upper
- Bolted tunnel bridge lower/upper
- Bolted brace cowl to shock tower assembly

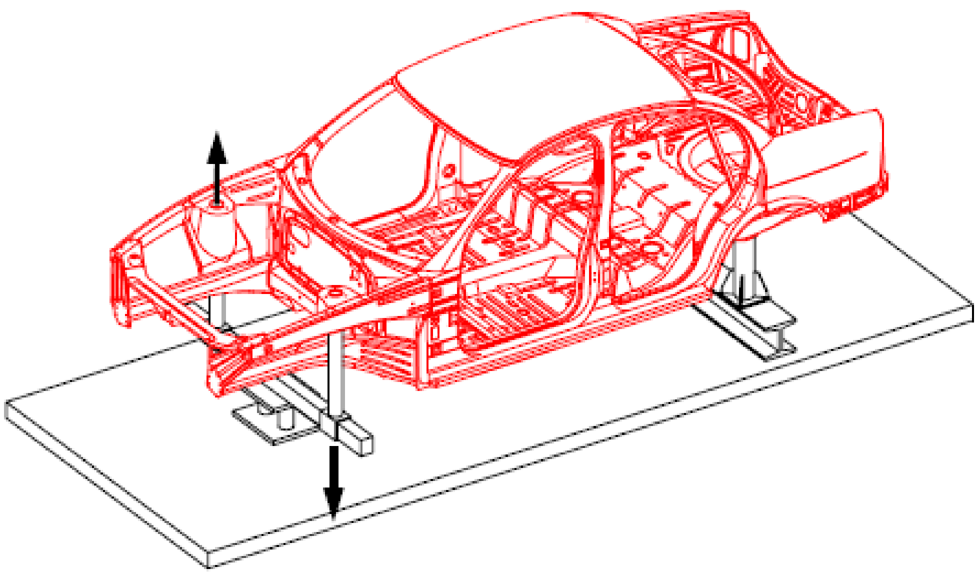


– Holding
  - Front: at panel skirt RH/LH
  - Rear: at plate rear spring upper

– Measurement
  - 12 stadia rods along the front rails, rockers, rear rails

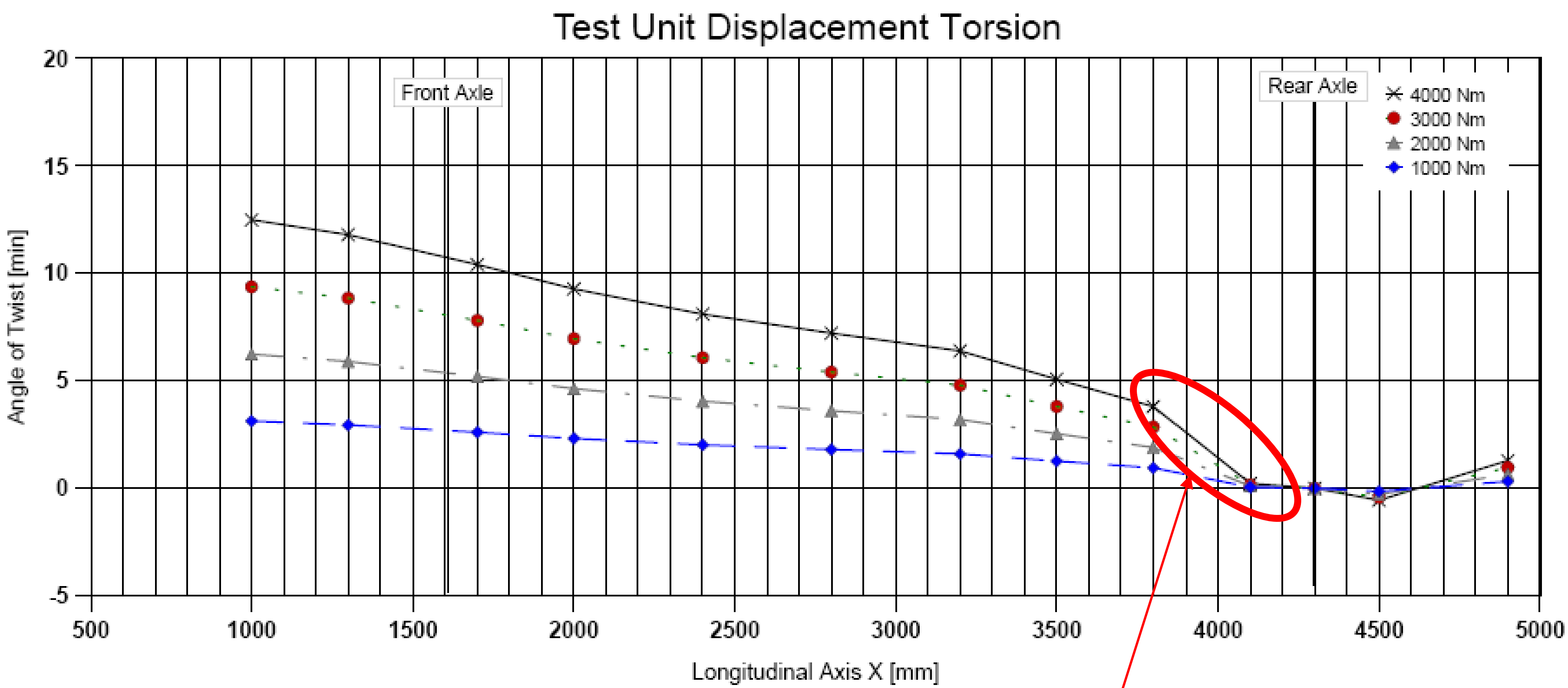
Static Torsion

- Constraint: two locations at the plate spring rear upper
- Load: panel skirt RH/LH by a scale beam, from M = 1000Nm to 4000Nm



Static Torsion: Test Results

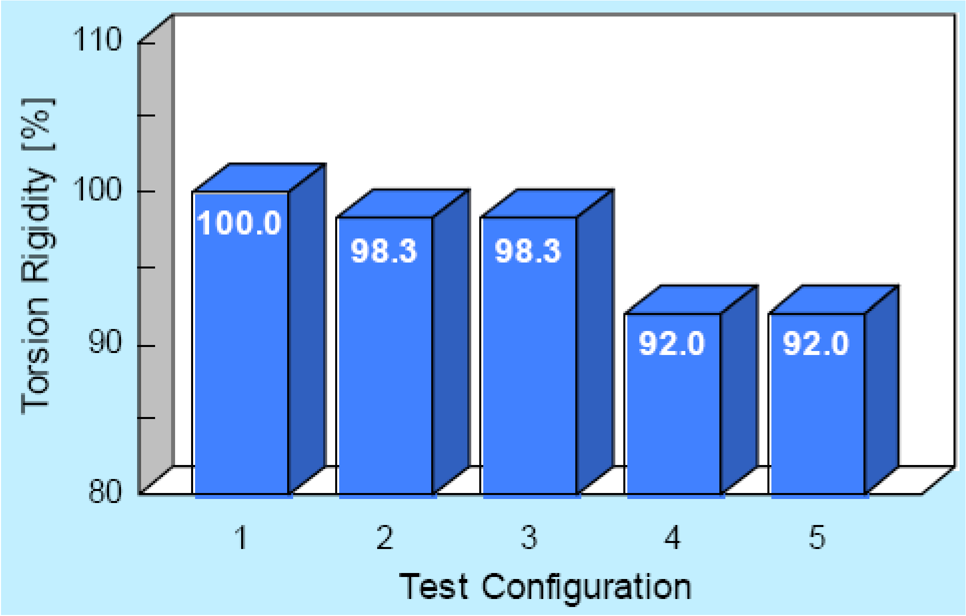
- With glass: 21,620 Nm/deg
- Without glass: 15,790 Nm/deg



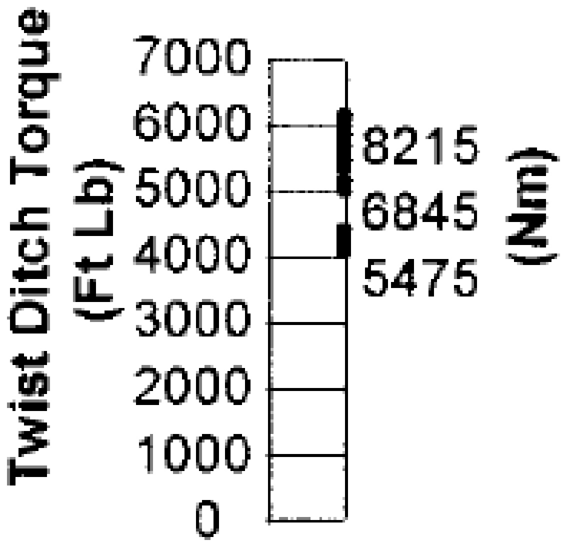
positive impact of the “member pass through” (Part No.090)

Static Torsion: impact of bonded and/or bolted parts

- 1. full configuration
- 2. as 1, but without braces radiator
- 3. as 2, but without radiator support upper
- 4. as 3, but without bolted brace cowl to shock tower assembly
- 5. as 4, but without tunnel bridge



Torsion Strength Benchmark Data



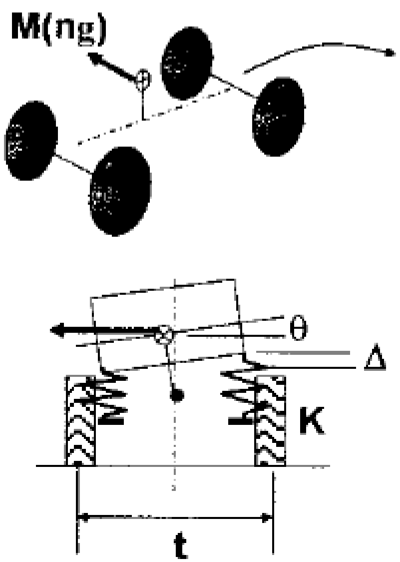
Range for 20 Cars from Small to Luxury Segments

5.2 Body Torsion Stiffness Requirement

- Body torsion test
  - Slope in the linear region of the applied couple vs. angular rotation
- Required functions for high torsional stiffness
  - Good handling property: torsionally stiff body relative to the suspension stiffness
    - Torsional stiffness: 10,000 Nm/°
  - Solid structural feel: minimize relative deformations which cause squeaks and rattles
    - Feel of solidness over road irregularities
    - Related to fundamental natural frequency of the body twisting mode: the higher, the more desirable solid feel
    - Desirable vehicle torsional frequency range: 22~25 Hz
    - Torsional stiffness (benchmarking): 12,000 Nm/°

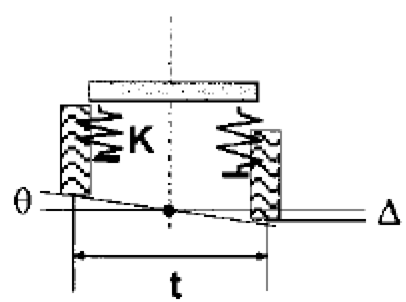
Good Handling Properties (1)

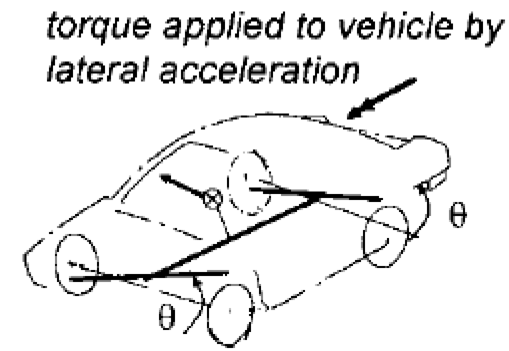
– Corner turn: roll on the suspension ride spring
– Weight transfer from the inside wheels to the outside wheels
– Affect the steering characteristics of the vehicle
– Suspension design: rigid body assumption → high torsional stiffness (much stiffer than the roll stiffness: 1000 Nm/°)



Roll Gain: Degrees of Vehicle Roll per g of Lateral Acceleration: θ/n

First order estimate of vehicle roll stiffness



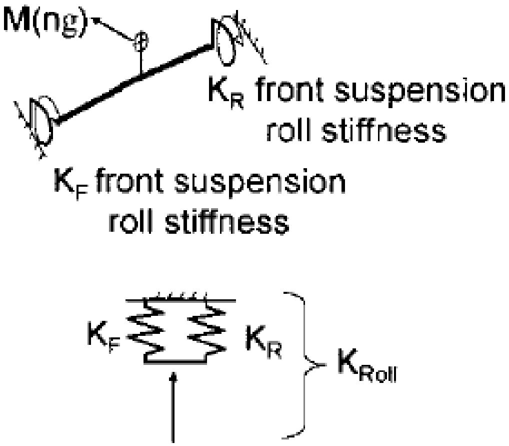


$$K_{RollVehicle} = K_{RollFront} + K_{RollRear} = \frac{t^2 K_{RideFront}}{2} + \frac{t^2 K_{RideRear}}{2}$$

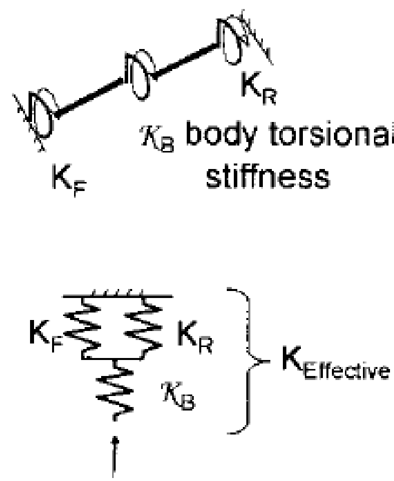
$$\left.\begin{array}{l} t = 1560mm \\ K_{Ride} = 23.4N/mm \end{array}\right\} \rightarrow K_{Roll} = 57,000Nm/rad = 1000Nm/\deg$$

Good Handling Properties (2)

- For typical passenger cars, K_{body} = 10,000 Nm/°



Ideally Rigid Body



Model with Body Torsional Stiffness

K_{eff} : stiffness with a torsionally flexible body

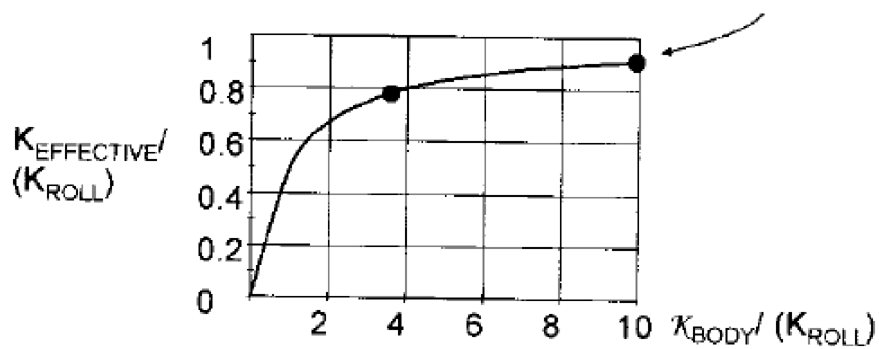
K_{roll} : suspension stiffness with a rigid body

K_B : body torsional stiffness

$$K_{eff} = \frac{K_{roll} K_B}{K_{roll} + K_B} \rightarrow \frac{K_{eff}}{K_{roll}} = \frac{1}{\frac{K_{roll}}{K_B} + 1} = \frac{1}{\frac{1}{\frac{K_B}{K_{roll}}} + 1}$$

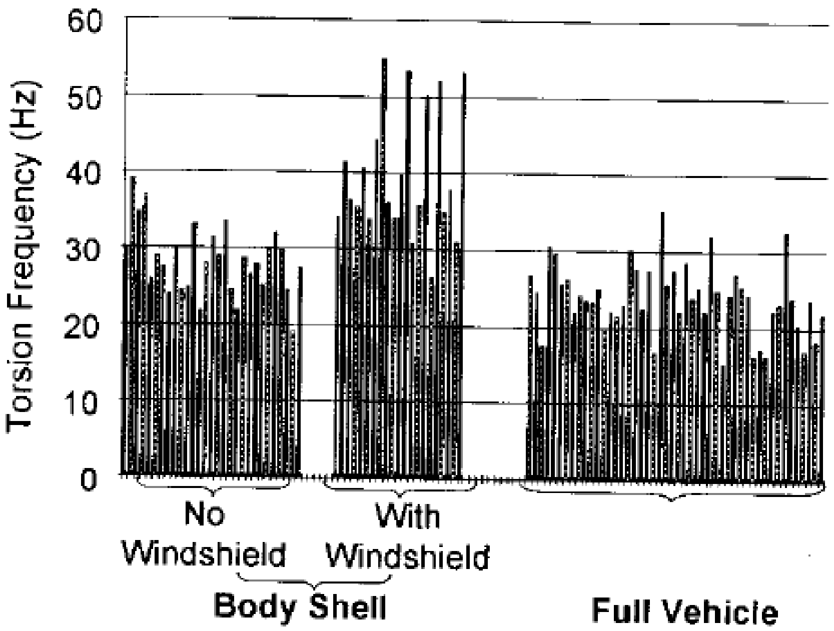
$$\frac{K_{eff}}{K_{roll}} = 0.9 \left(\text{wish to approach } 1 \right) \rightarrow K_B = 10 K_{roll}$$

<u>Only suspension roll rate</u>

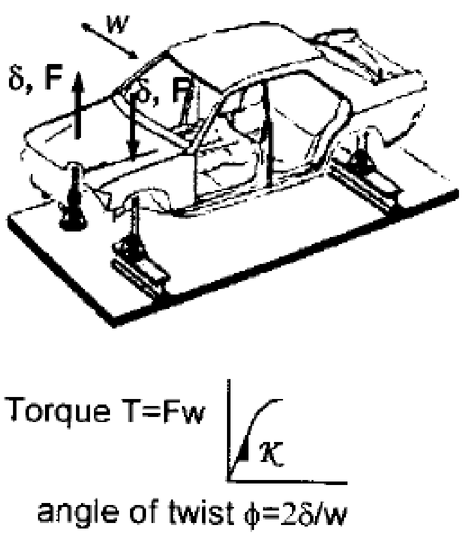


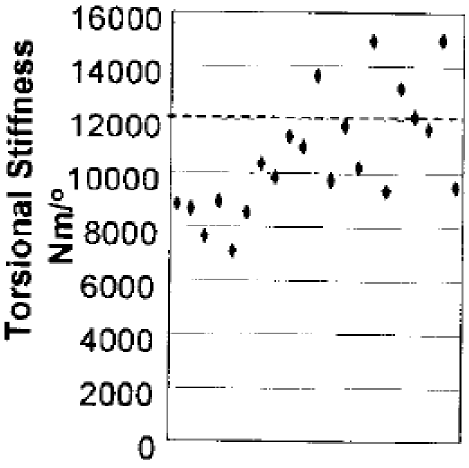
Benchmark Data

- Torisional frequency



- Torsional stiffness

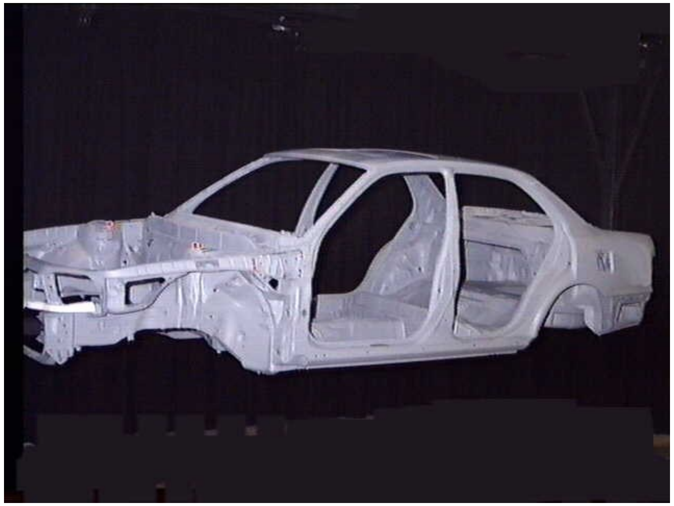


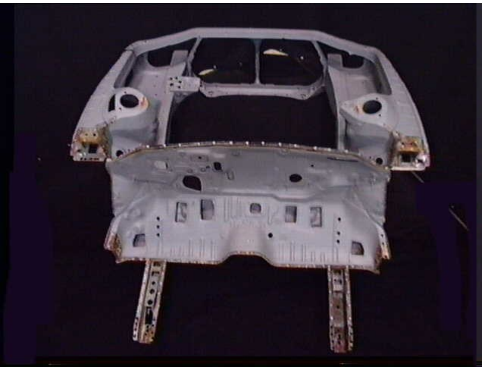


Torsion Stiffness with Glass

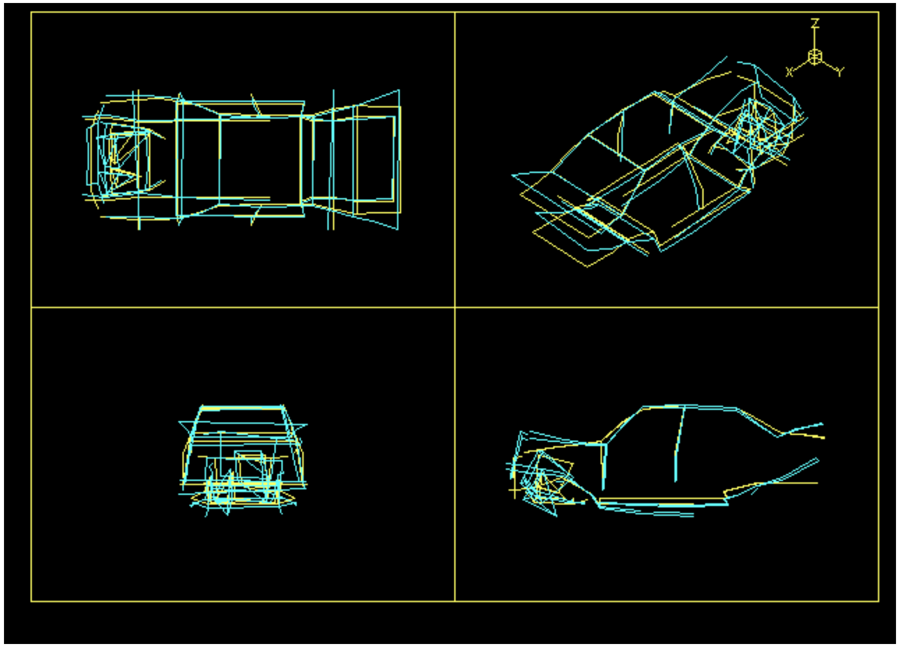
Body-In-White: TOYOTA-CAMRY

- Nameplate CAMRY - Model XLE -Year 1992
  Style 4 DR, Vehicle class MID-SIZE
  Overall length (m) 4.77, Overall width (m) 1.77,
  Overall height (m) 1.4, Wheelbase (m) 2.62
  Base price ($) 20,508, Seating capacity 5 , Curb weight (Kg) 1493
  Body/frame UNIBODY, Body material STEEL
  Fuel economy (MPG) 18/24, Engine 3.0L, V6,
  TRANS DOHC, Chassis layout FRONT,
  Transmission 4 SP AUTO
  Suspension front MacPHERSON STRUT,
  Suspension rear INDEPENDENT DUAL-LINK

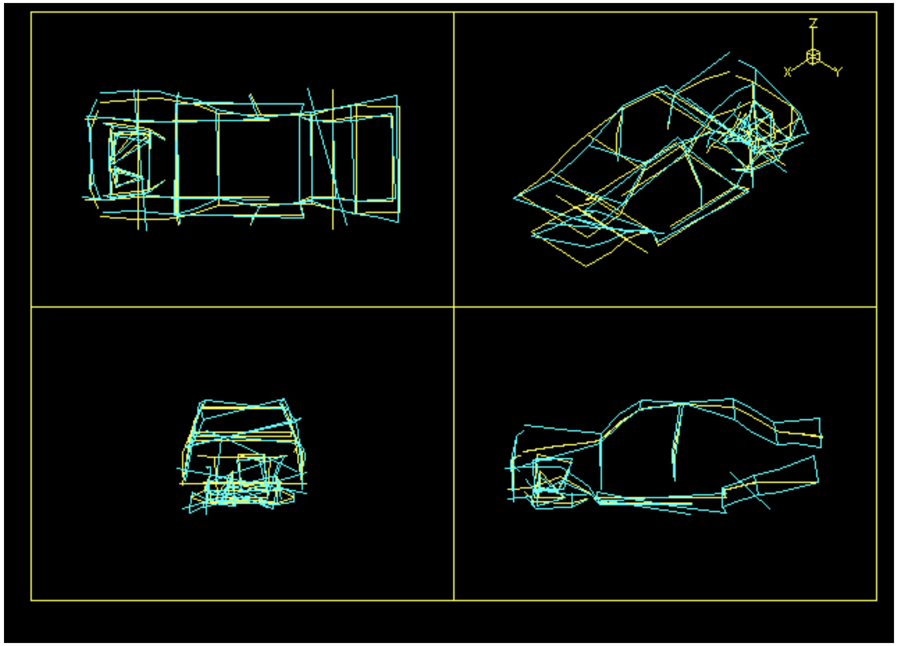




Vibration: TOYOTA-CAMRY



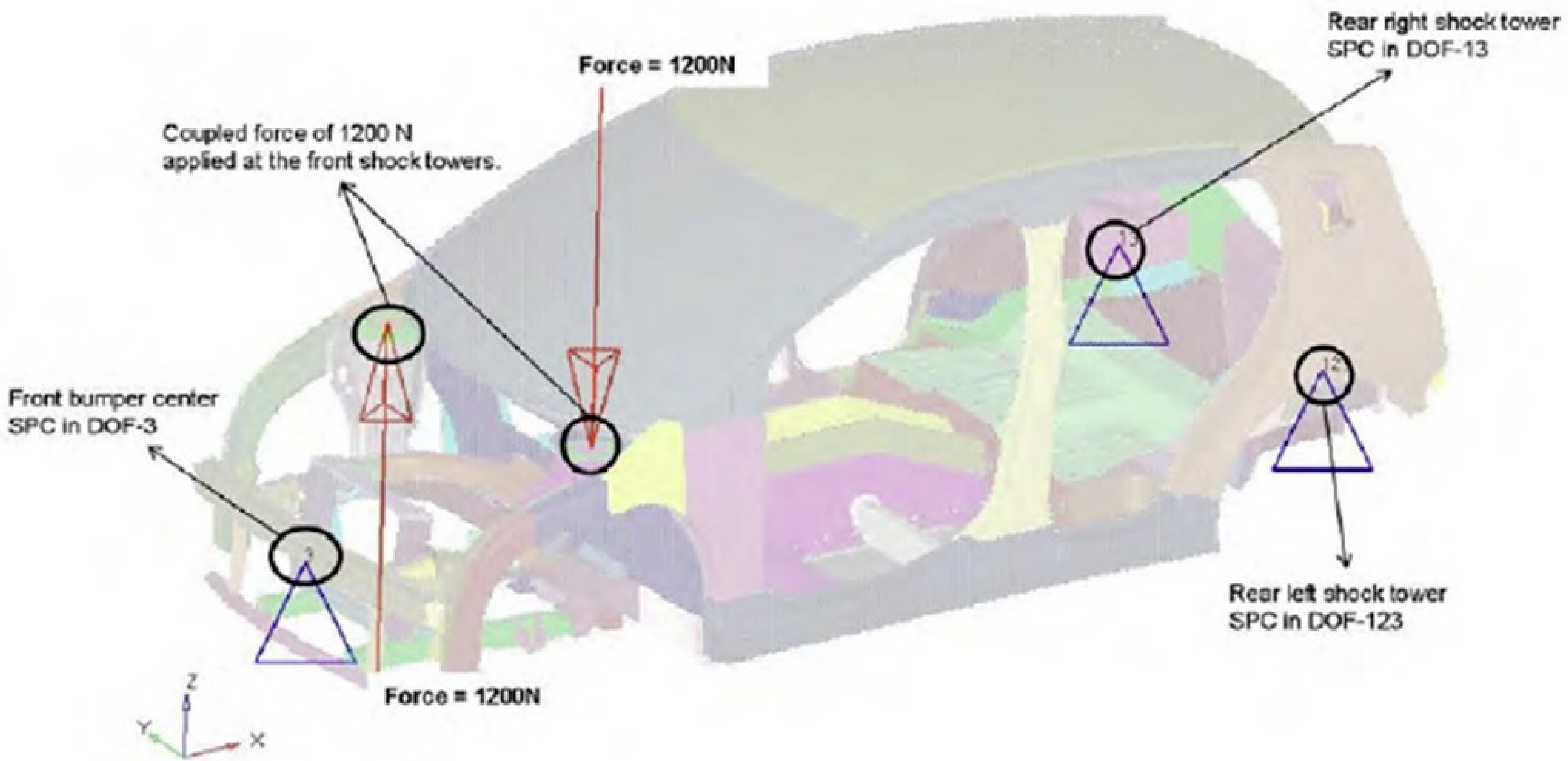
Bending



Torsion

Torsion Stiffness

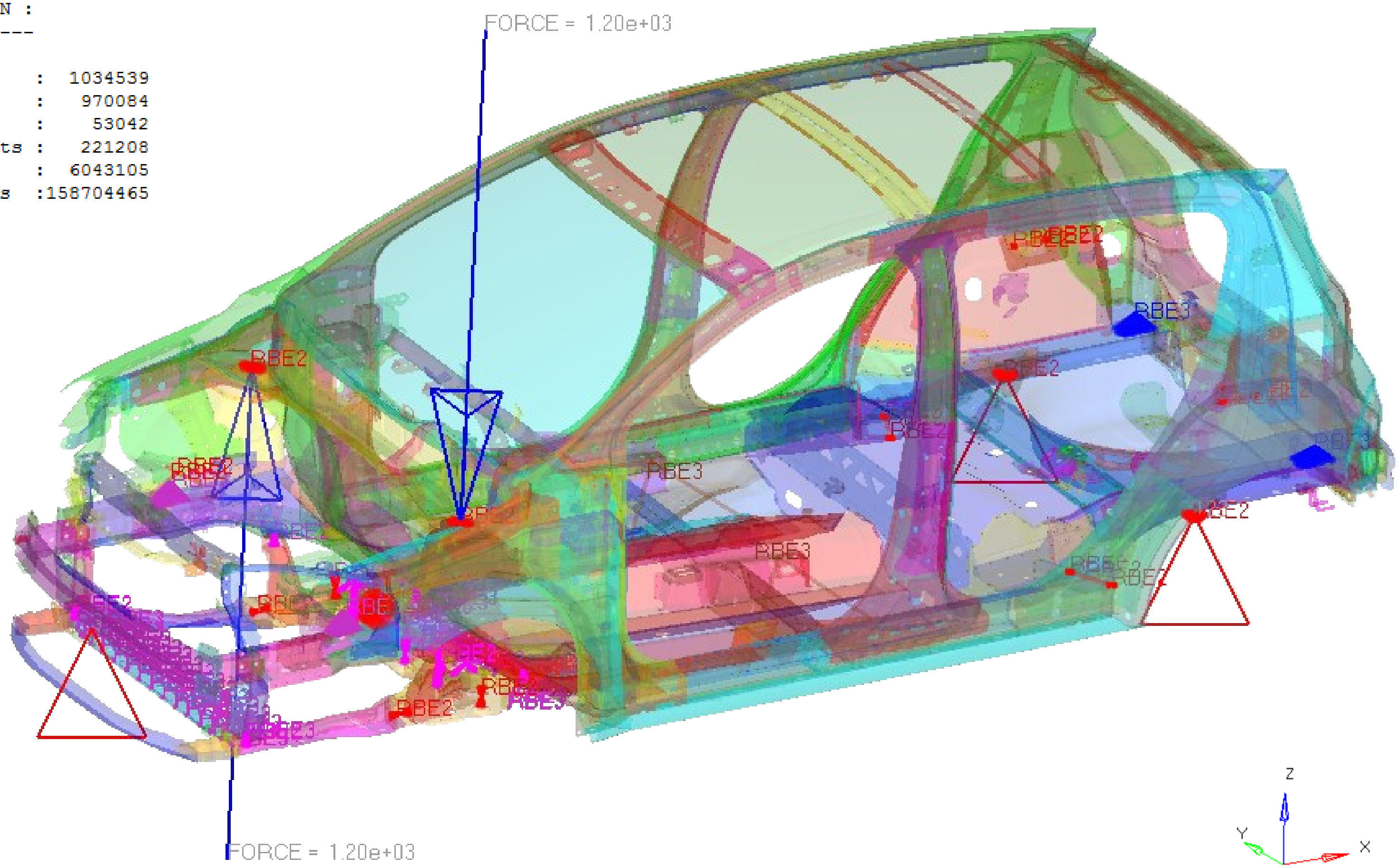
- Constraints and Loading in FSV Report



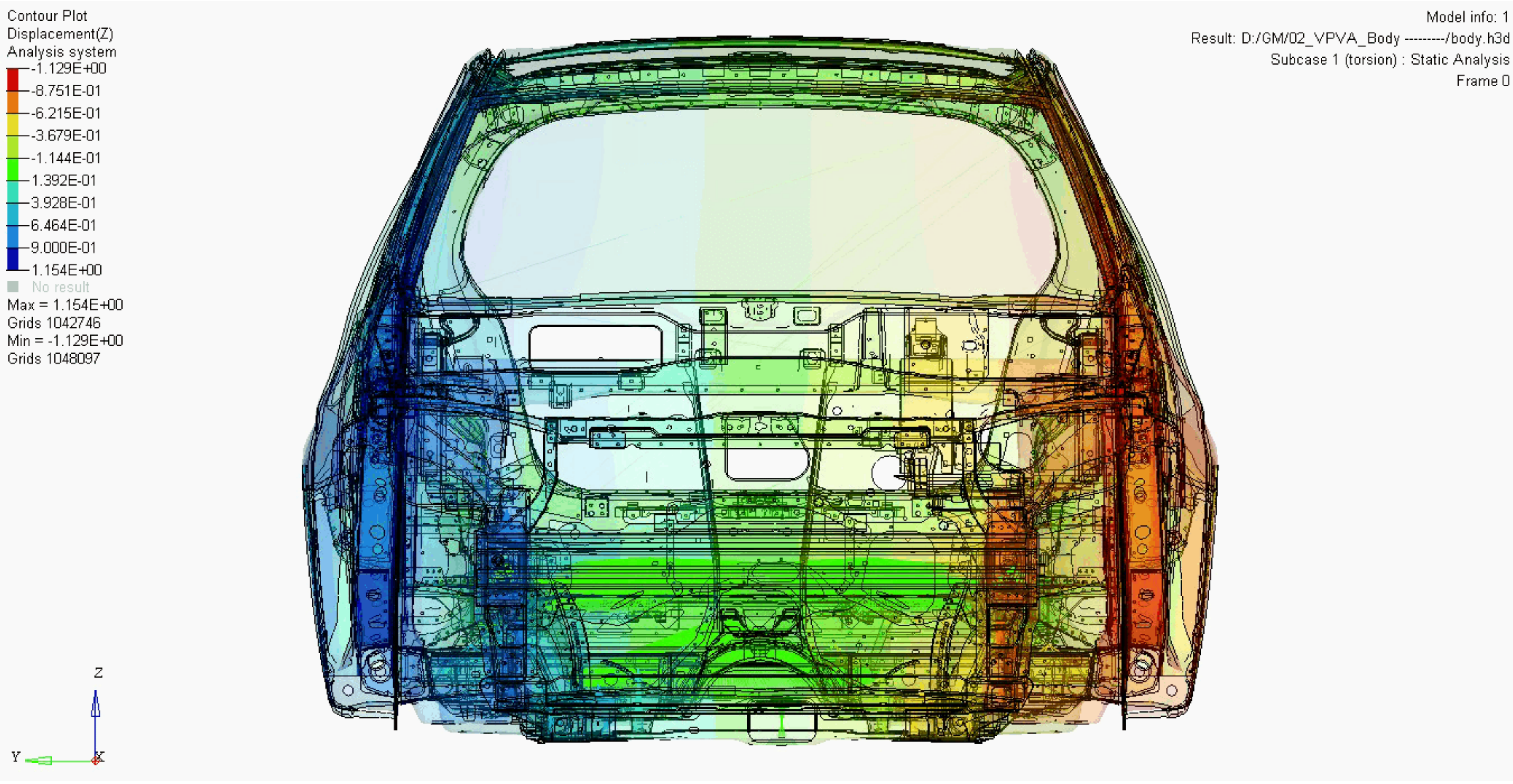
Torsion Stiffness

- Constraints and Loading in Hypermesh

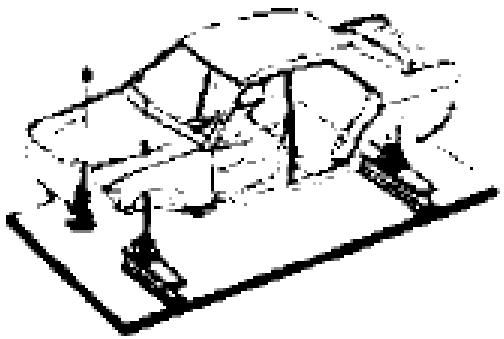
```
FINITE ELEMENT MODEL DATA INFORMATION :
---------------------------------------

  Total # of Grids (Structural)        :  1034539
  Total # of Elements                  :   970084
  Total # of Rigid Elements            :    53042
  Total # of Rigid Element Constraints :   221208
  Total # of Degrees of Freedom        :  6043105
  Total # of Non-zero Stiffness Terms  :158704465


  Element Type Information
  ------------------------

   CHEXA    Elements   :     12119
   CPENTA   Elements   :        98
   CQUAD4   Elements   :    900965
   CTRIA3   Elements   :     55437
   PLOTEL   Elements   :      1465

  Load and Boundary Information
  -----------------------------

   FORCE Sets         :         2
   SPC   Sets         :         2

  Material and Property Information
  ---------------------------------

   PSOLID Cards       :        12
   PSHELL Cards       :       420
   MAT1   Cards       :        34
```



Torsion Stiffness



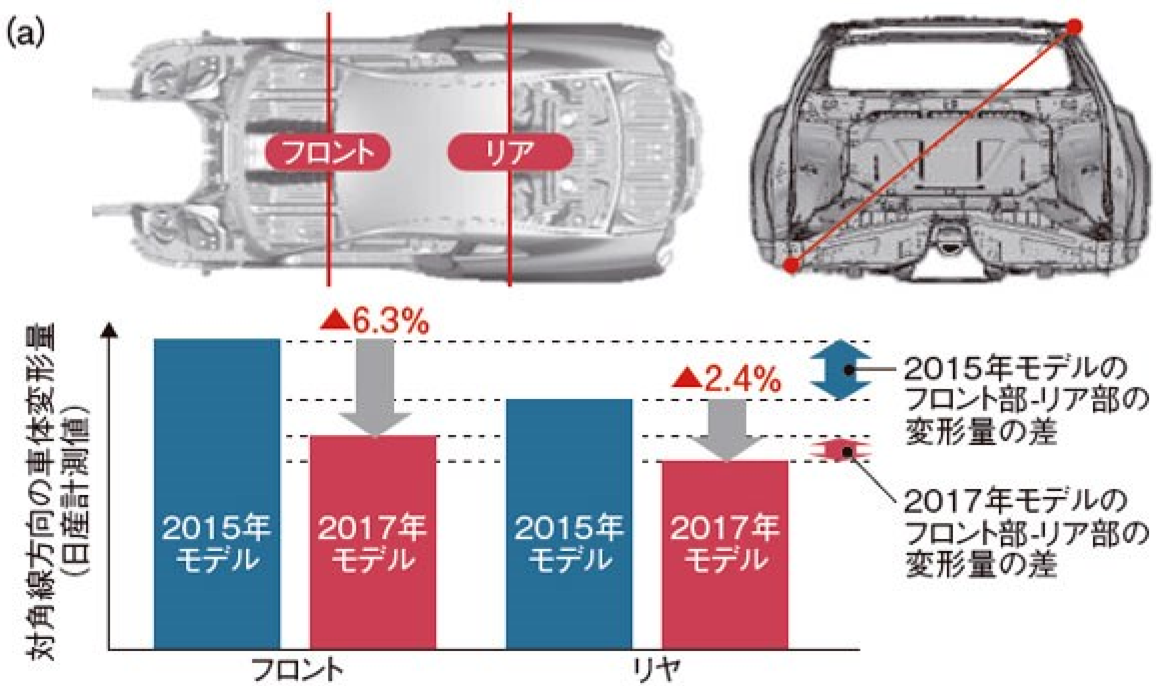
Typical Torsional Requirements: Midsize Vehicle

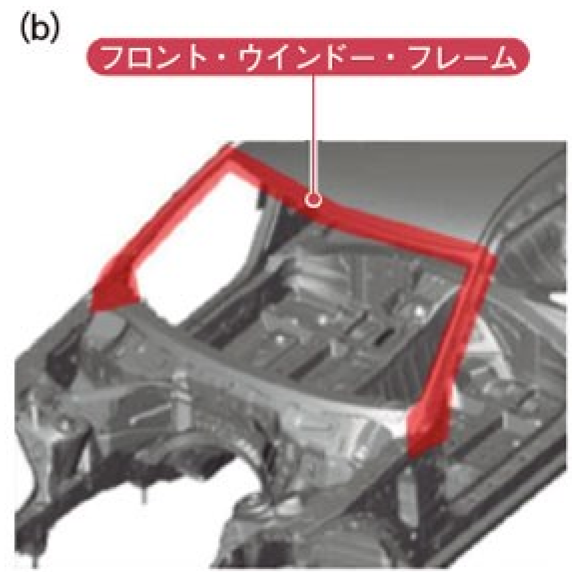


Restraints at Suspension Attachments

Torsion Stiffness	**Torsion Strength**
Nominal Value Stiffness = 12000 Nm/o	Nominal Value T= 6250Nm no permanent deformation

Nissan GT-T (2016.05.10)



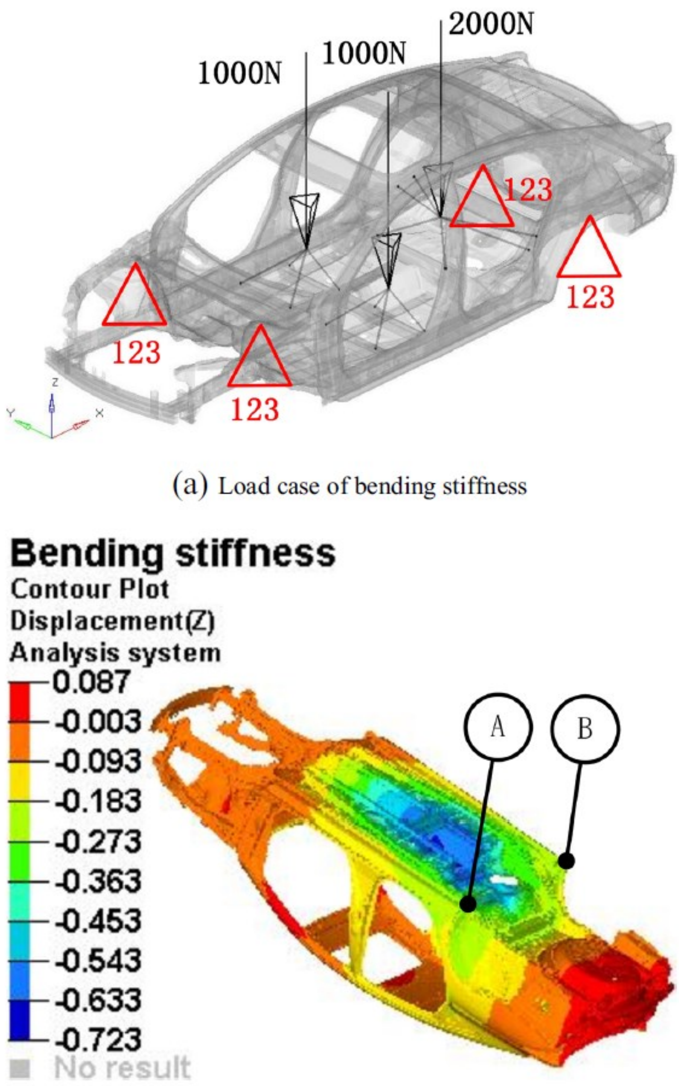


Structural and Multidisciplinary Optimization (2018) 58:1823–1843
https://doi.org/10.1007/s00158-018-1986-3

INDUSTRIAL APPLICATION

Multi-objective lightweight and crashworthiness optimization for the side structure of an automobile body

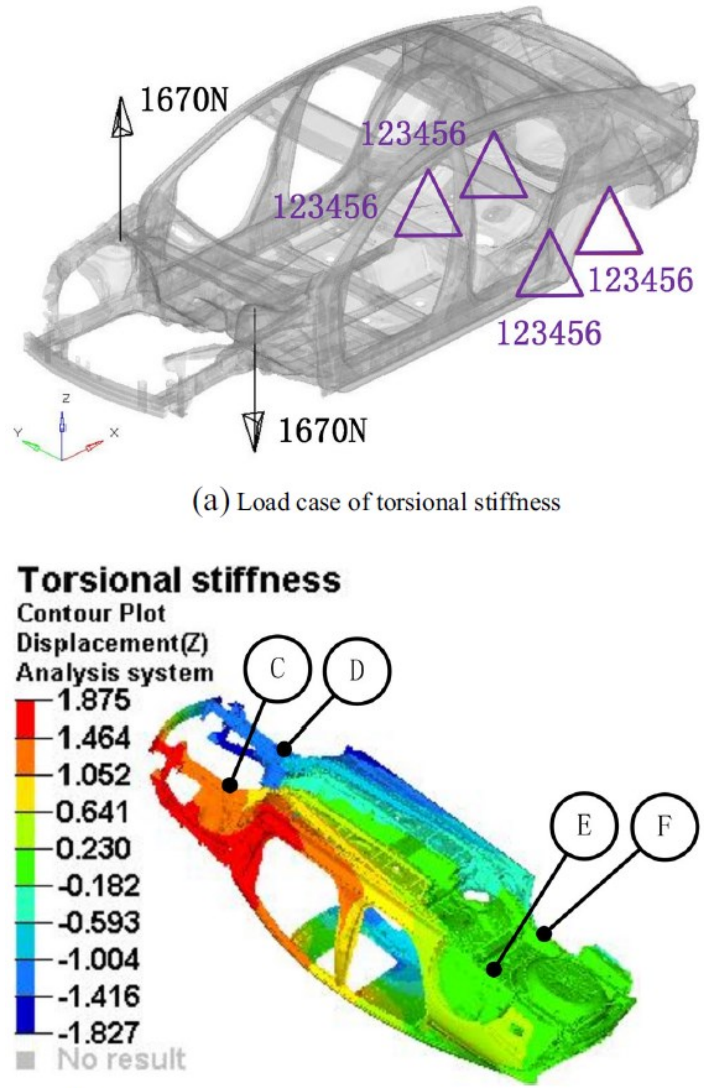
Feng Xiong [1,2] · Dengfeng Wang [1] · Shuming Chen [1] · Qiang Gao [3] · Shudong Tian [4]



(a) Load case of bending stiffness

(b) Measuring nodes for calculation of bending stiffness

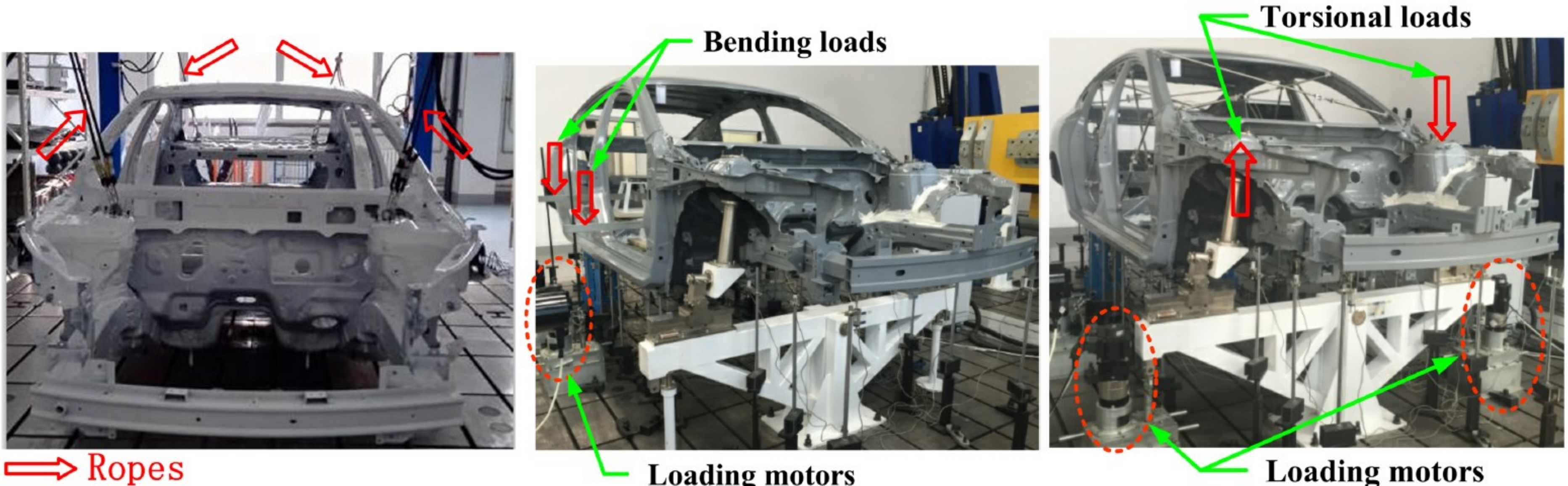
Fig. 5 FE model of bending stiffness of automobile body



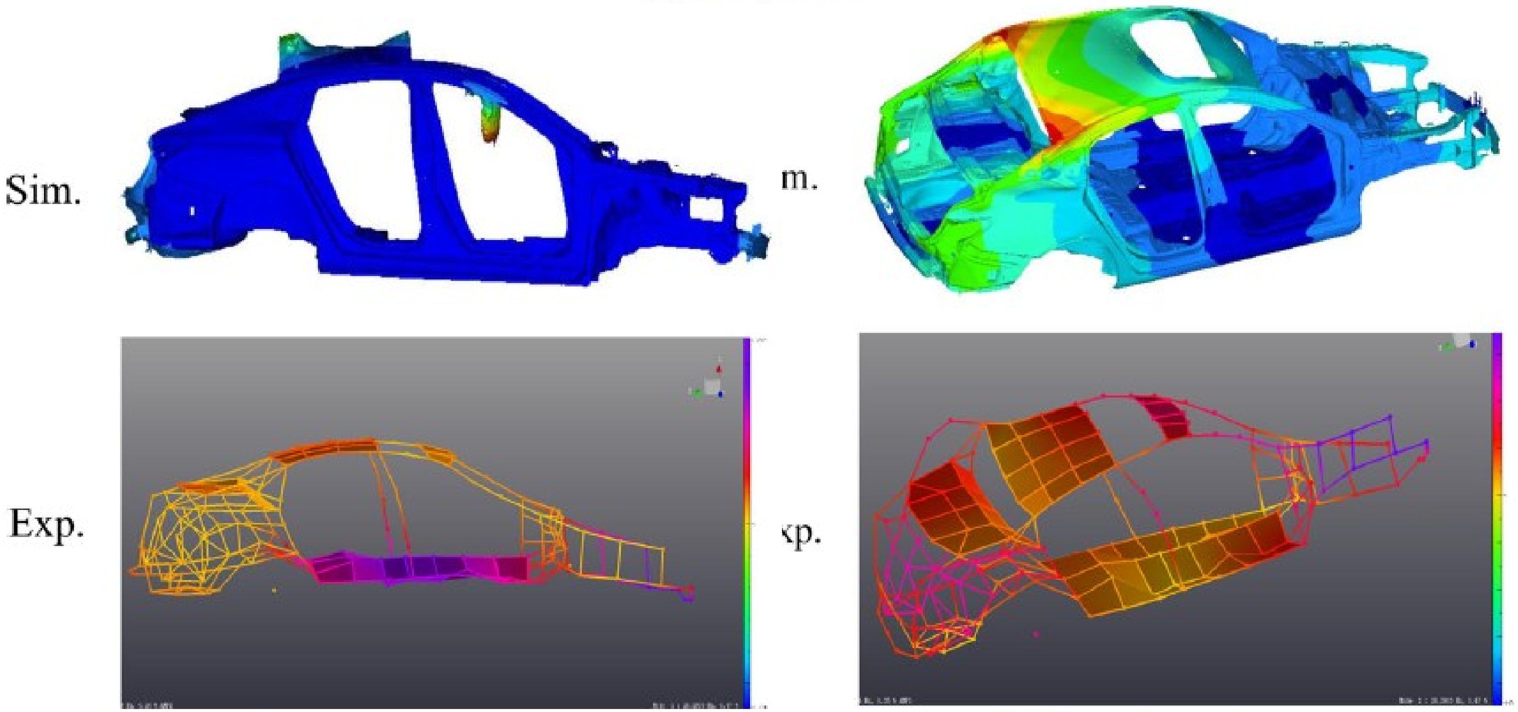
(a) Load case of torsional stiffness

(b) Measuring nodes for calculation of torsional stiffness

Fig. 6 FE model of torsional stiffness of automobile body



(a) Modal frequencies (b) Bending stiffness (c) Torsional stiffness



(b) First-order bending (a) First-order torsion

$$S_B = \frac{F}{(z_1 + z_2)/2}$$

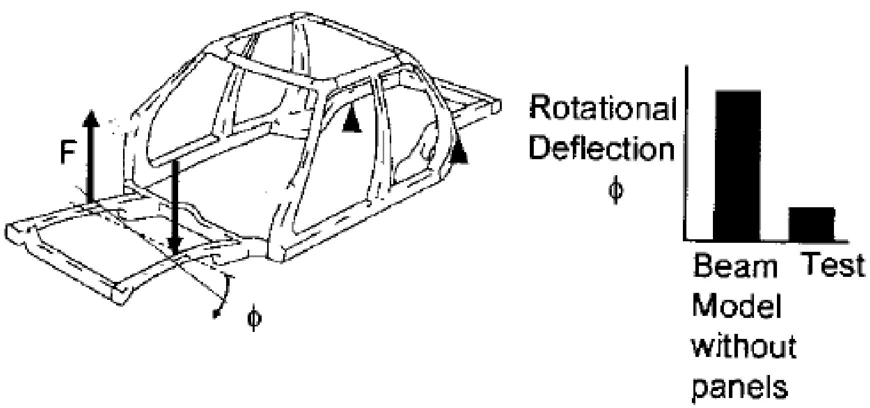
$$\phi = \left(\frac{Z_f}{Y_f} - \frac{Z_r}{Y_r}\right) * \frac{180}{\pi}; S_T = Torque/\phi$$

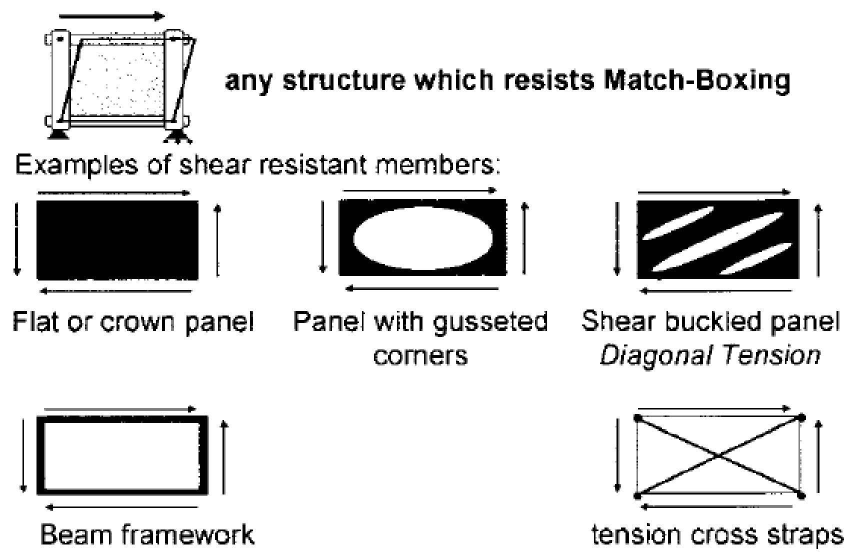
where z_1 and z_2 respectively denote the absolute displacement of measuring nodes A and B in Z direction (Fig. 5b); F denotes the summation of loading forces in Z direction (Fig. 5a); Z_f and Y_f respectively denote the relative displacement of the two measuring nodes on the front rails (C and D) in Z direction and their lateral distance along Y-axis (Fig. 6b); Z_r and Y_r respectively denote the relative displacement of the two measuring nodes on the rear rails (E and F) in Z direction and their lateral distance along Y-axis (Fig. 6b); ϕ denotes the twist angle of the front end relative to the rear end of the automobile body; *Torque* denotes the loaded torque that formed by a force couple as shown in Fig. 6a. For the bending stiffness, the average Z-axial displacement of measuring nodes A and B induced by loading forces are employed for calculation to eliminate experimental errors. In contrast, the twist angle (ϕ) of the front end relative to the rear end of the automobile body

Stiffness indicators	Simulation	Experiment	Error (%)
f_T/Hz	34.72	35.56	−2.36
f_B/Hz	53.34	56.85	−6.17
$S_T/N \cdot m \cdot \deg^{-1}$	15,260.4	15,208.5	0.34
$S_B/N \cdot mm^{-1}$	18,200.2	18,152.6	0.26

5.3 Load Path Analysis: Global Torsion

- Understand how global body requirements flow down to loads on structural elements
- Idealized structure as a framework of beams
  - Torsional stiffness: 10~30% of experimental values
- Dominant structure in reaction torsion loading
  - Surface: shear resistant members

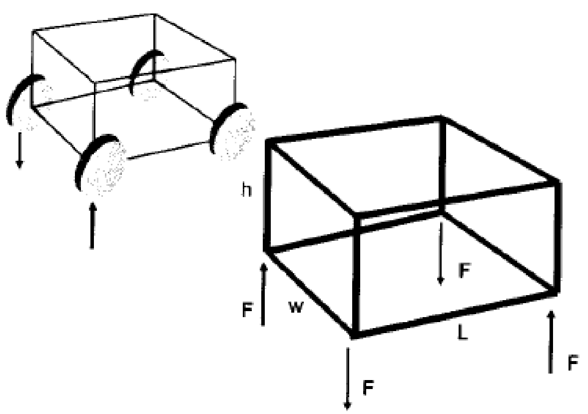


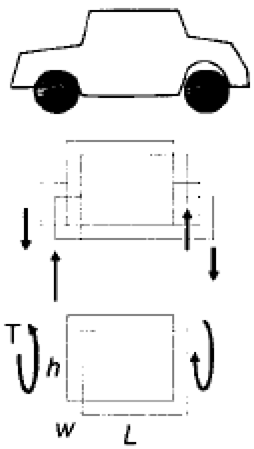


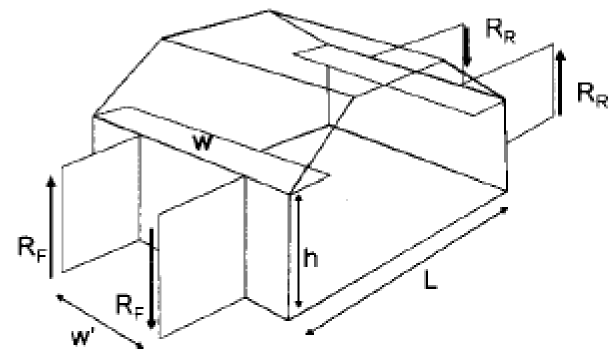
sideframe, rear hatch opening, windshield ring

Models in Torsion

- Monocoque box model
- Passenger cabin model
- Structural surface and bar model





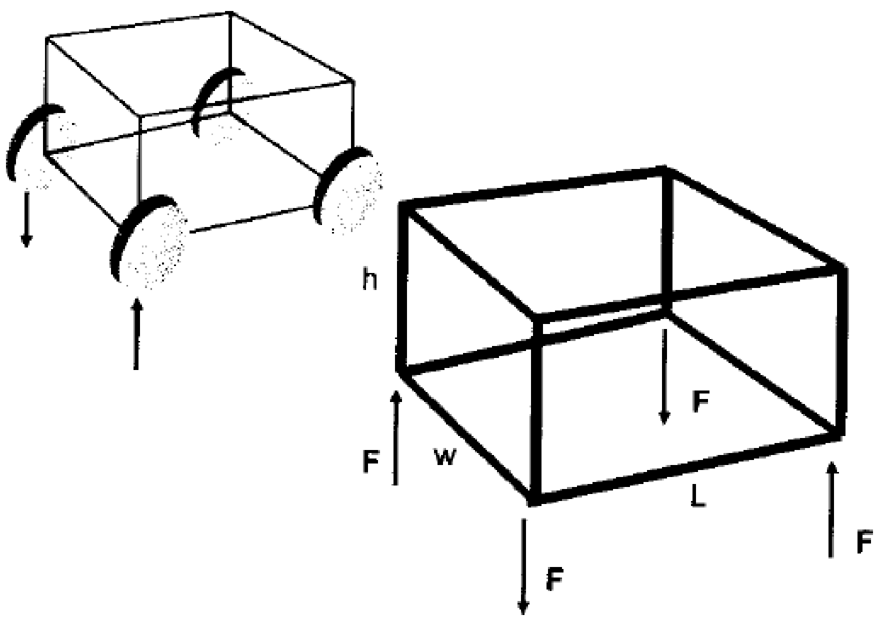


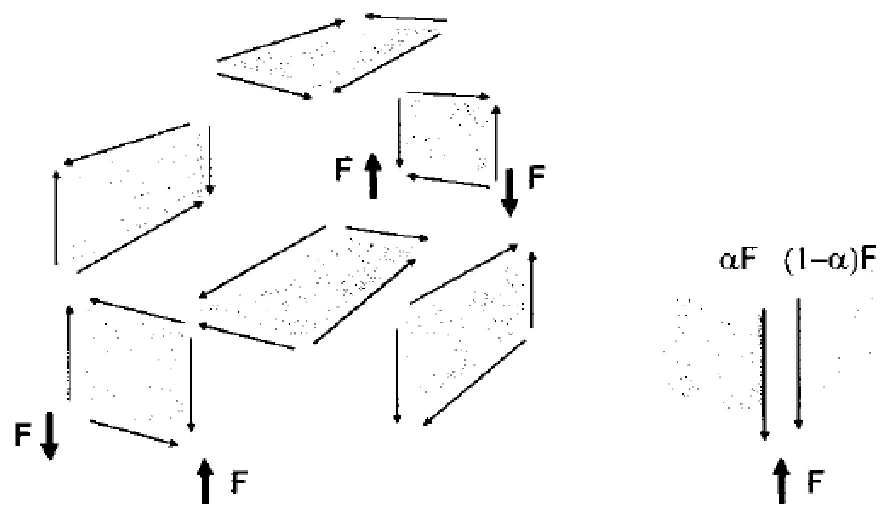
Simple Box Model

- All surfaces are loaded
- Internal loads are independent of material properties
- Each surface is necessary to react the applied torsional couple: removal of any single surface will not allow the required equilibrium and the box will collapse
- Shear flow is equal for all edges

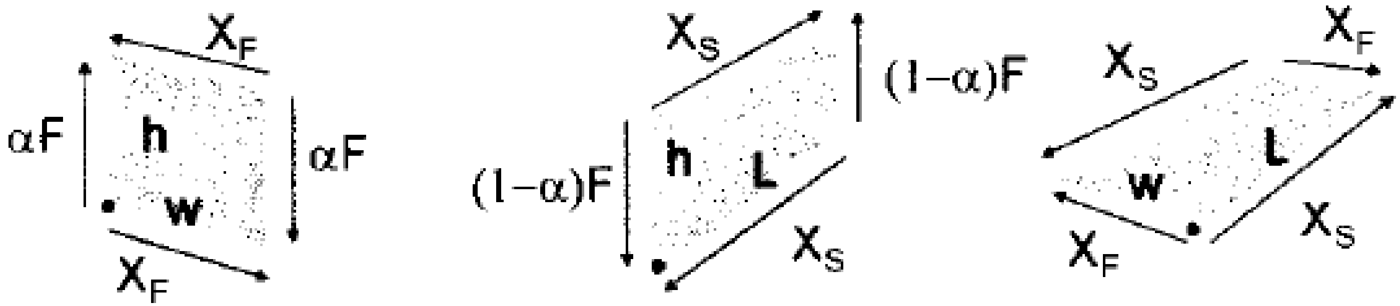
α: load taken by front surface

$1-\alpha$: load taken by side surface





Box Model Internal Loads



$$w\alpha F = hX_F$$

$$X_F = \alpha \frac{w}{h} F$$

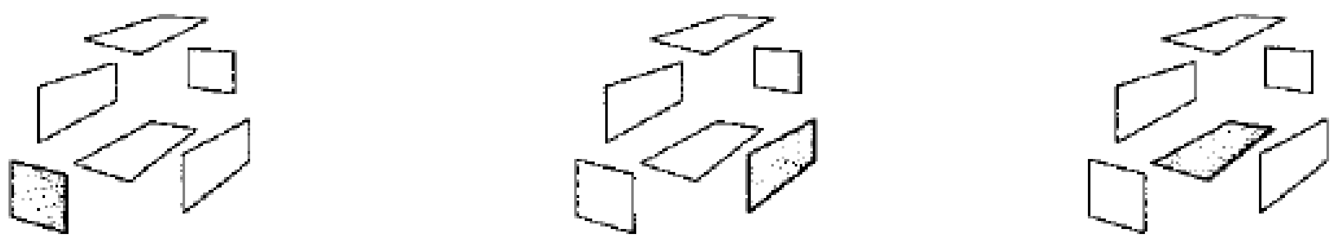
$$L(1-\alpha)F = hX_S$$

$$X_S = (1-\alpha)\frac{L}{h} F$$

$$LX_F = wX_S$$

$$\alpha \frac{w}{h} LF = (1-\alpha)\frac{L}{h} wF$$

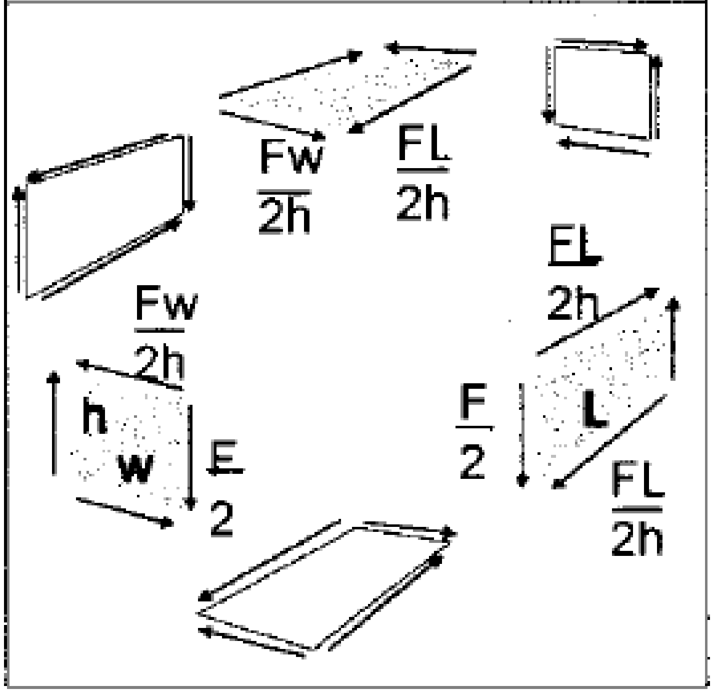
$$\alpha = (1-\alpha), \quad \alpha = 1/2$$



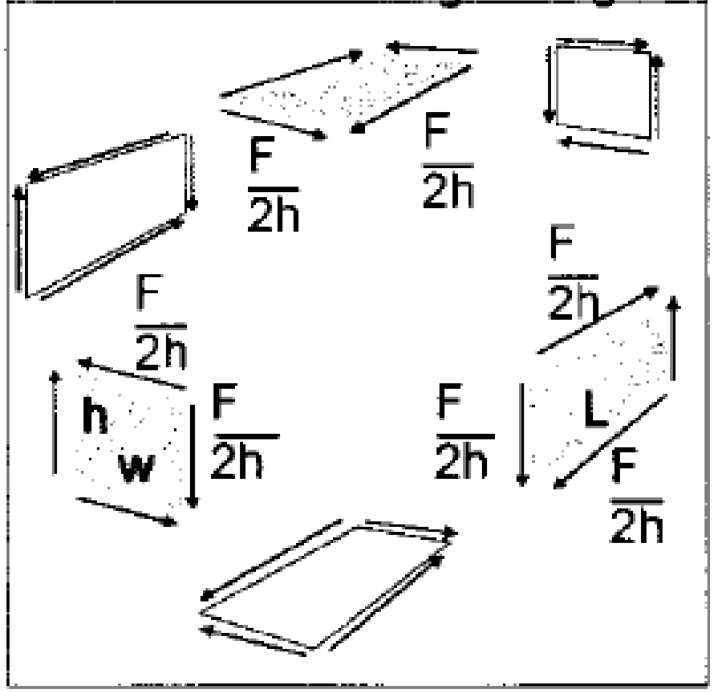
Front Surface | Left Side Surface | Bottom Surface

Monocoque Box in Torsion

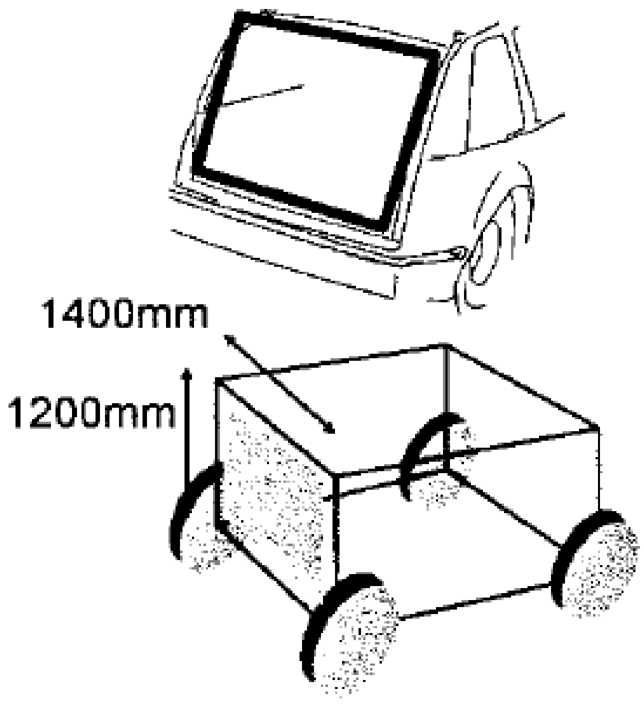
Edge Forces
Twisting forces, F, at corners



Shear Flow
q=Shear Flow = Edge Force / Edge Length



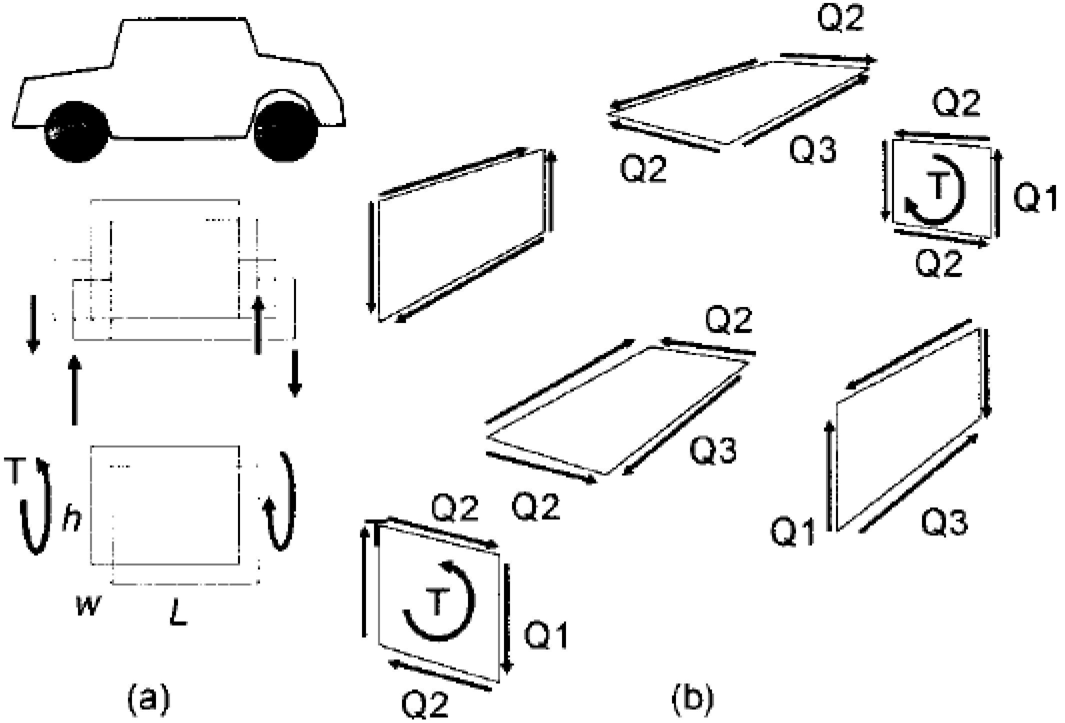
Example: Van Rear Hatch Opening



Twist Ditch Torque=$7x10^6$Nmm

- Determine shearing loads which need to be reacted by the rear hatch structure.

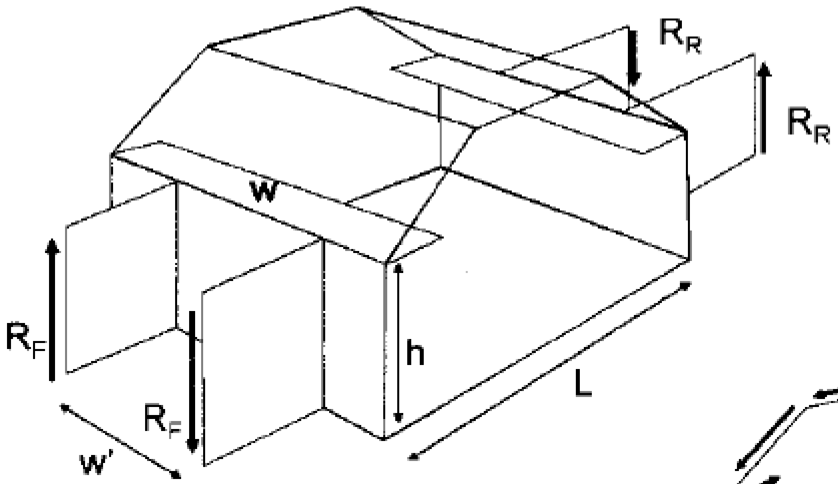
Passenger Cabin Internal Loads



$$\left.\begin{array}{l} +wQ_1 + hQ_2 \qquad\qquad = T \text{ (front)} \\ \qquad -LQ_2 + wQ_3 = 0 \text{ (top)} \\ -LQ_1 \qquad\quad + hQ_3 = 0 \text{ (side)} \end{array}\right\} \rightarrow \begin{bmatrix} w & h & 0 \\ 0 & -L & w \\ -L & 0 & h \end{bmatrix} \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{bmatrix} = \begin{bmatrix} T \\ 0 \\ 0 \end{bmatrix} \rightarrow \mathbf{AQ} = \mathbf{T}$$

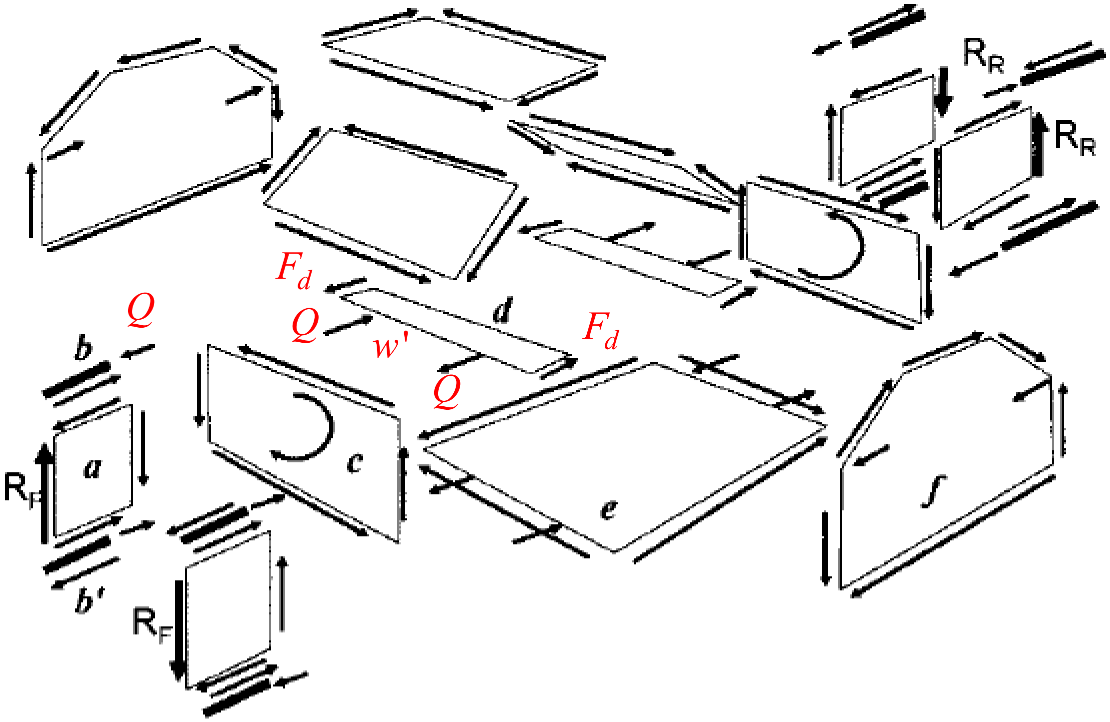
$$\mathbf{Q} = \mathbf{A}^{-1}\mathbf{T} \rightarrow \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{bmatrix} = \frac{1}{2whL} \begin{bmatrix} hL & h^2 & -hw \\ wL & -wh & w^2 \\ L^2 & Lh & Lw \end{bmatrix} \begin{bmatrix} T \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} T/2w \\ T/2h \\ TL/2wh \end{bmatrix}$$

Structural Surface and Bar Model

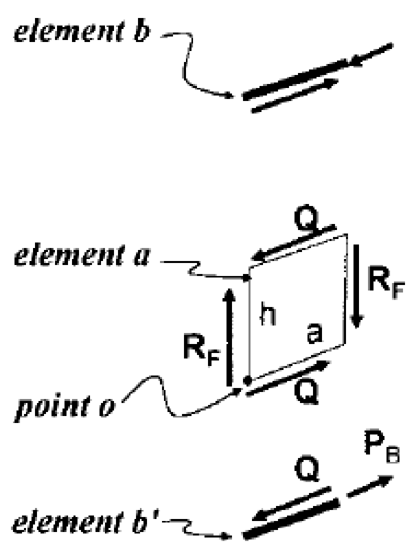


$$R_F = \frac{T_{max}}{w'}$$

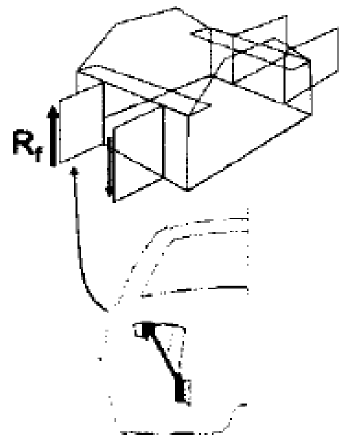
<u>more realistic model</u>

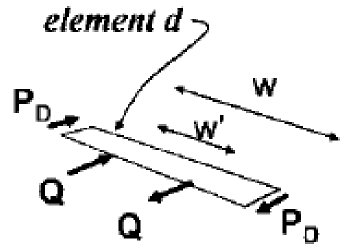


Internal Loads

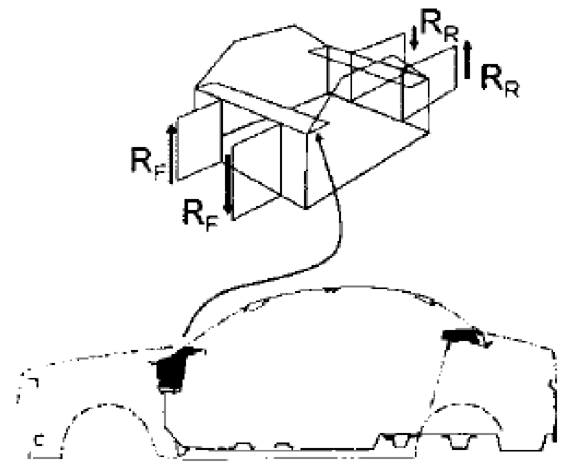


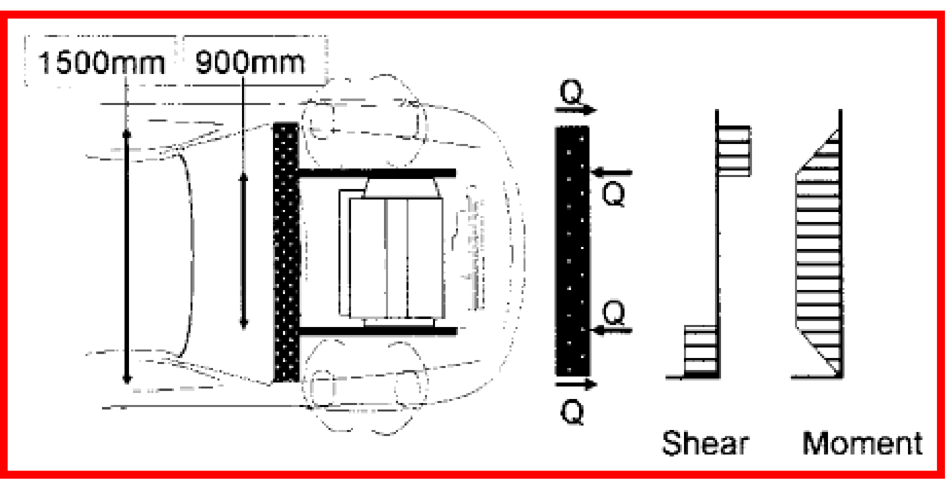
$$\Sigma M_o = 0$$
$$aR_F = hQ$$
$$Q = \frac{a}{h} R_F$$
$$P_B = Q$$

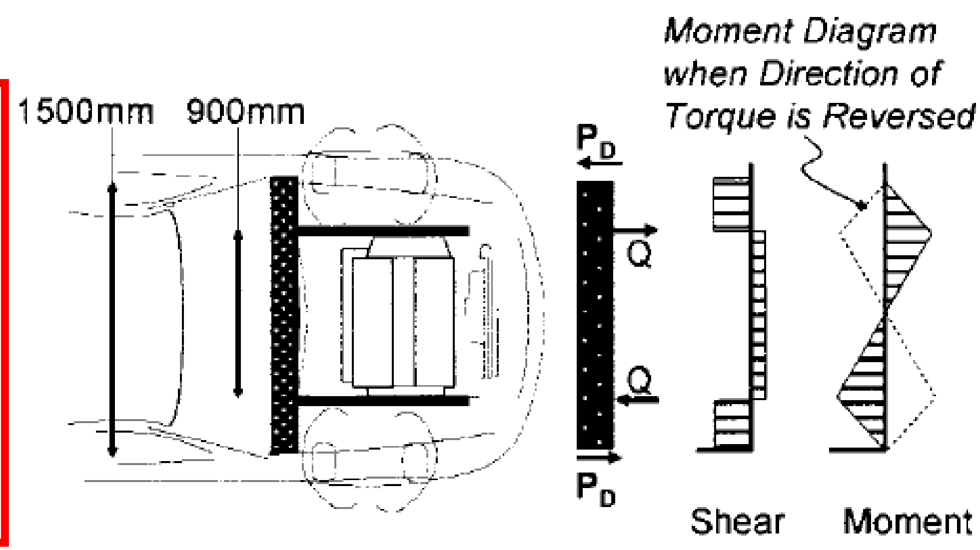




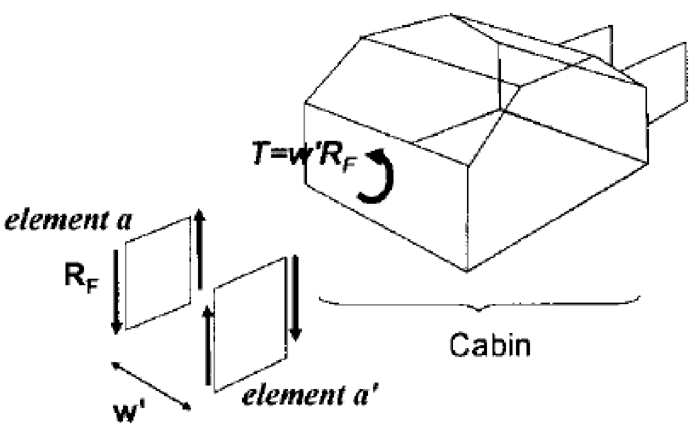
$$\Sigma M = 0$$
$$wP_D = w'Q$$
$$P_D = \frac{w'}{w} Q$$

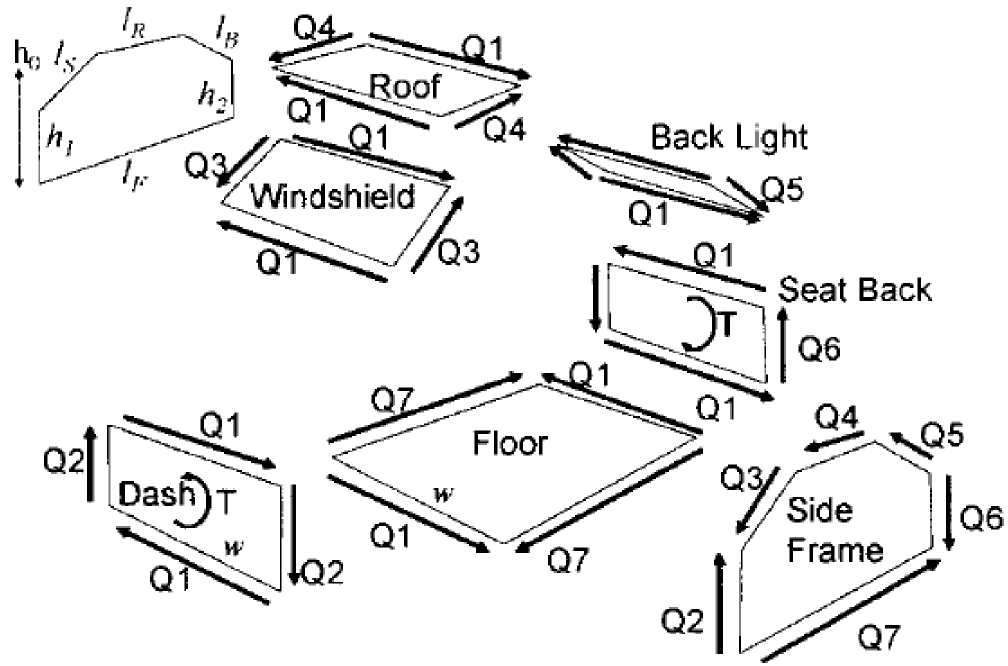




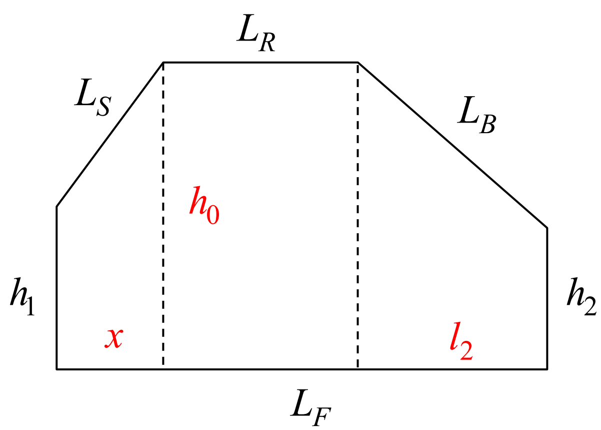


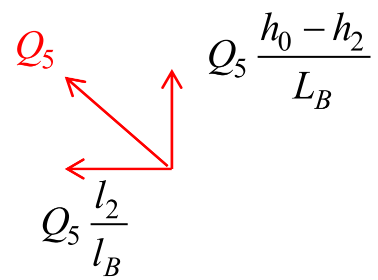
Shear Loads on Cabin Panels





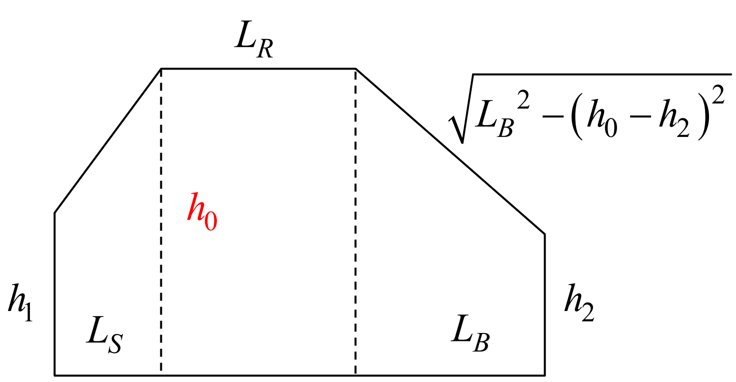
$$
\begin{bmatrix}
h_1 & w & 0 & 0 & 0 & 0 & 0 \\
l_S & 0 & -w & 0 & 0 & 0 & 0 \\
l_R & 0 & 0 & -w & 0 & 0 & 0 \\
l_B & 0 & 0 & 0 & -w & 0 & 0 \\
h_2 & 0 & 0 & 0 & 0 & w & 0 \\
l_F & 0 & 0 & 0 & 0 & 0 & -w \\
0 & 0 & 0 & (h_0 - h_1) & \left[l_F(h_0 - h_2) + l_2(h_2 - h_1)\right]/l_B & -l_F & h_1
\end{bmatrix}
\begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \\ Q_5 \\ Q_6 \\ Q_7 \end{bmatrix}
=
\begin{bmatrix} T \\ 0 \\ 0 \\ 0 \\ T \\ 0 \\ 0 \end{bmatrix}
\begin{matrix} \text{dash} \\ \text{windshield} \\ \text{roof} \\ \text{backlight} \\ \text{rear seat panel} \\ \text{floor} \\ \text{side frame} \end{matrix}
$$

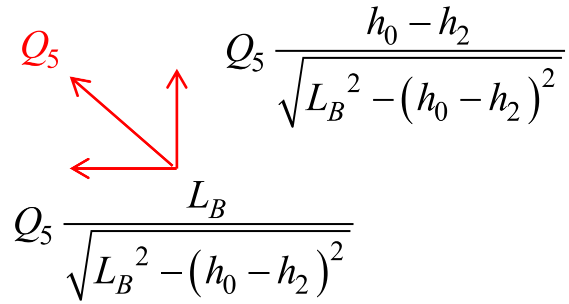




$$L_S{}^2 = x^2 + \left(h_0 - h_1\right)^2 \rightarrow x = \sqrt{L_S{}^2 - \left(h_0 - h_1\right)^2}$$

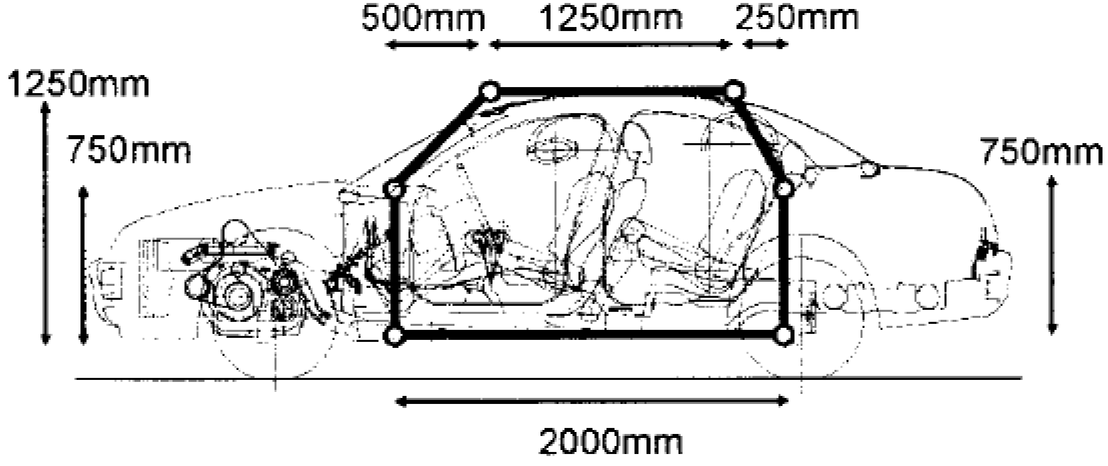
$$x + L_R + L_2 = L_F \rightarrow L_2 = L_F - L_R - \sqrt{L_S{}^2 - \left(h_0 - h_1\right)^2}$$





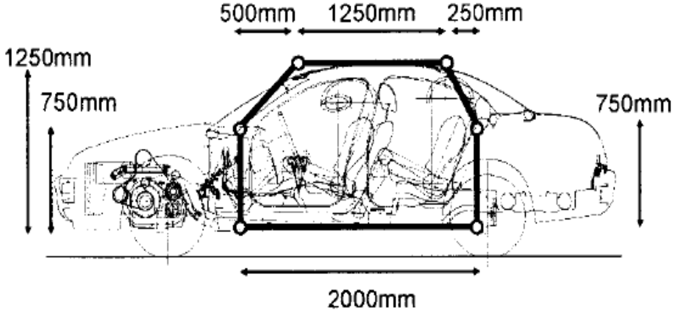
Example: Midsize Sedan Data

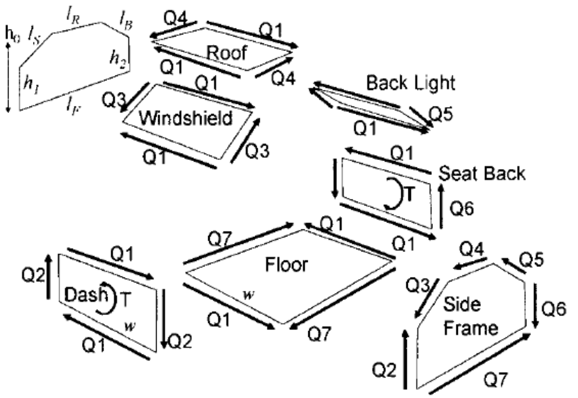
- Determine internal shear loads
  - Track = 1560 mm
  - Twist ditch torque = 7,730 Nm



Example: Shear Loads

Torque	7730000
track	1560
h0	1250
h1	750
h2	750
Ls	707
Lr	1250
Lb	559
Lf	2000





A							T	Q	q
750	1560	0	0	0	0	0	7730000	3343	2.142758
707	0	−1560	0	0	0	0	0	3348	
1250	0	0	−1560	0	0	0	0	1515	2.142758
559	0	0	0	−1560	0	0	0	2678	2.142758
750	0	0	0	0	1560	0	7730000	1198	2.142758
2000	0	0	0	0	0	−1560	0	3348	
0	0	0	500	1789	−2000	750	0	4286	2.142758

5.4 Analysis of Body Torsional Stiffness

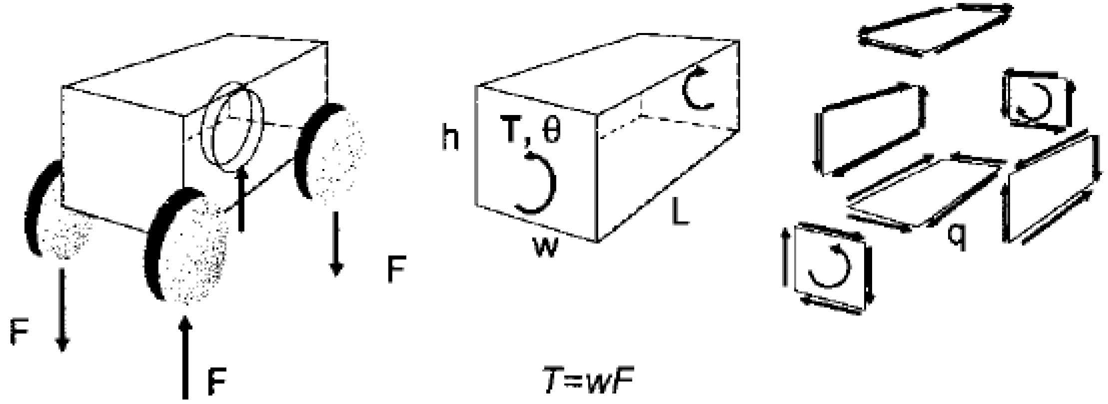
- Shear strain energy of a surface

$$e=\int\frac{\tau\gamma}{2}dV=\int\frac{\tau^2}{2G}dV=\frac{\left(q/t\right)^2}{2G}\left(abt\right)=q^2\,\frac{ab}{2\left(Gt\right)}$$

- Energy balance for torque loaded box

$$\frac{1}{2}T\theta=\sum_{\text{all surfaces}}\frac{1}{2}q^2\left[\frac{ab}{\left(Gt\right)}\right]_i\xrightarrow{q=\frac{F}{2h}=\frac{T/w}{2h}=\frac{T}{2wh}}\frac{1}{2}T\theta=\sum_{\text{all surfaces}}\frac{1}{2}\left(\frac{T}{2wh}\right)^2\left[\frac{ab}{\left(Gt\right)}\right]_i$$

$$\theta=T\left(\frac{1}{2wh}\right)^2\sum_{\text{all surfaces}}\left[\frac{ab}{\left(Gt\right)}\right]_i\rightarrow K=\frac{T}{\theta}=\left(2wh\right)^2\frac{1}{\sum_{\text{all surfaces}}\left[\frac{ab}{\left(Gt\right)}\right]_i}$$

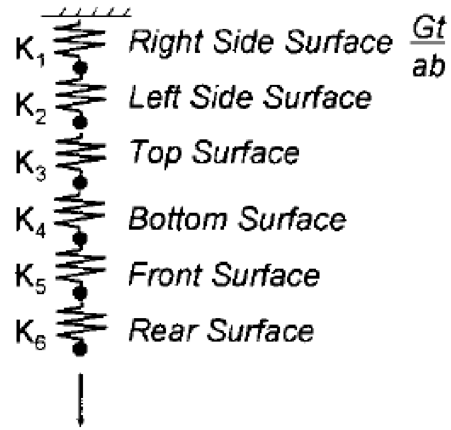


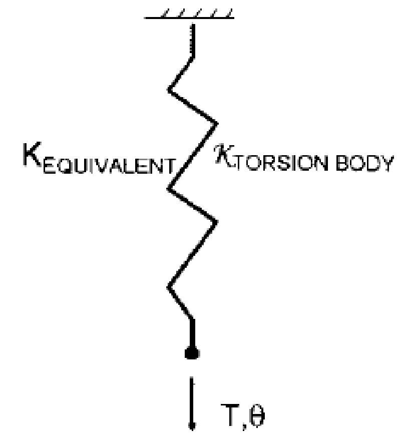
Series Spring Analogy

- Consider a set of six linear springs in series

$$K_{eq} = \frac{1}{\sum_{i=1}^{6} \left[1/K_i \right]} \leftrightarrow K = \frac{T}{\theta} = \left(2wh\right)^2 \frac{1}{\sum_{\text{all surfaces}} \left[\frac{ab}{(Gt)} \right]_i}$$

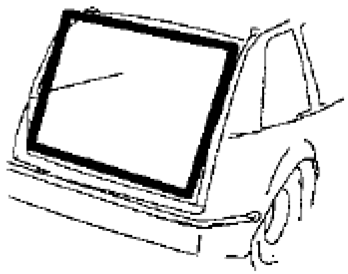
$$\Rightarrow K_i \leftrightarrow \left(\frac{Gt}{ab} \right)_{\text{surface } i}$$

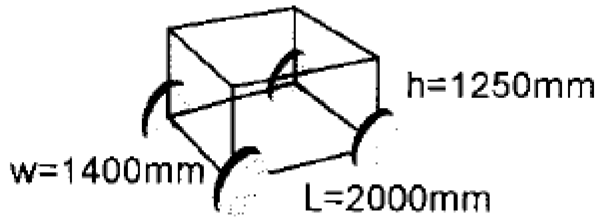




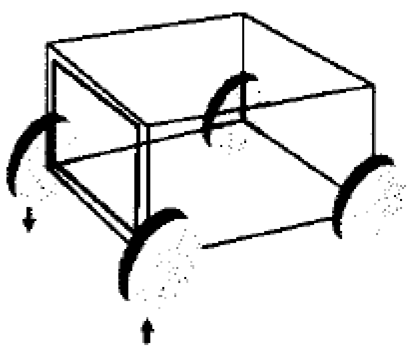
- How to increase torsional stiffness?
  - Identify which surfaces is the most flexible: lowest $\left[\frac{(Gt)}{ab} \right]$
  - Increase the stiffness of the least stiff spring

Example: Box Van





All Panels Steel
G=80,000N/mm²
t=1 mm

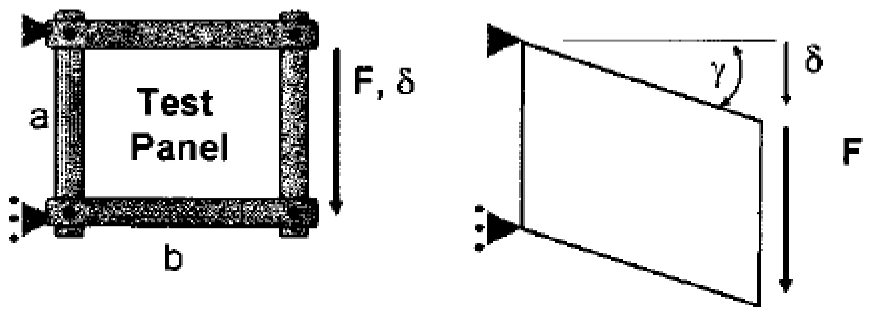


- K = 6.95×10^{10} Nm/rad = 1,200,000 Nm/°
- About 100 times stiffer than measured data
- Why?
  - Ideal flat plate assumption: surfaces remain perfectly flat during loading
  - Reality: out-of-plane shape, holes and cut-outs, framework of beams with flexible joints
- Effective shear stiffness: $(Gt)_{eff}$

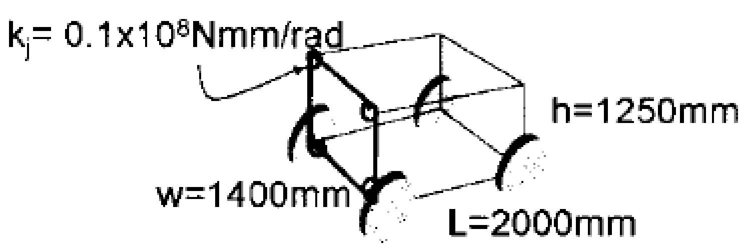
Effective Shear Stiffness

- Test panel in a pinned frame fixture
  - $(Gt)_{eff}$: shear stiffness for a panel
  - S: measured stiffness (slope of load vs. deflection curve)
    - Physical test / FEM
  - a: panel dimension of the side load is applied
  - b: adjacent side dimension

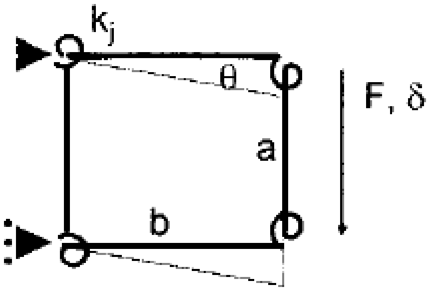
$$G = \frac{\tau}{\gamma} \xrightarrow{\tau = \frac{F}{at},\ \gamma = \frac{\delta}{b}} (Gt)_{eff} =$$



Example: Van Hatch Opening (1)



All Panels Steel
G=80,000N/mm²
t=1 mm



$$\underbrace{\frac{1}{2}F\delta}_{\text{work done}} = \underbrace{4\left(\frac{1}{2}K_j\theta^2\right)}_{\text{energy stored in the joints}} \xrightarrow{\theta=\frac{\delta}{b}} S=\frac{F}{\delta}=\frac{4K_j}{b^2} \rightarrow (Gt)_{eff}=\frac{4K_j}{ab}$$

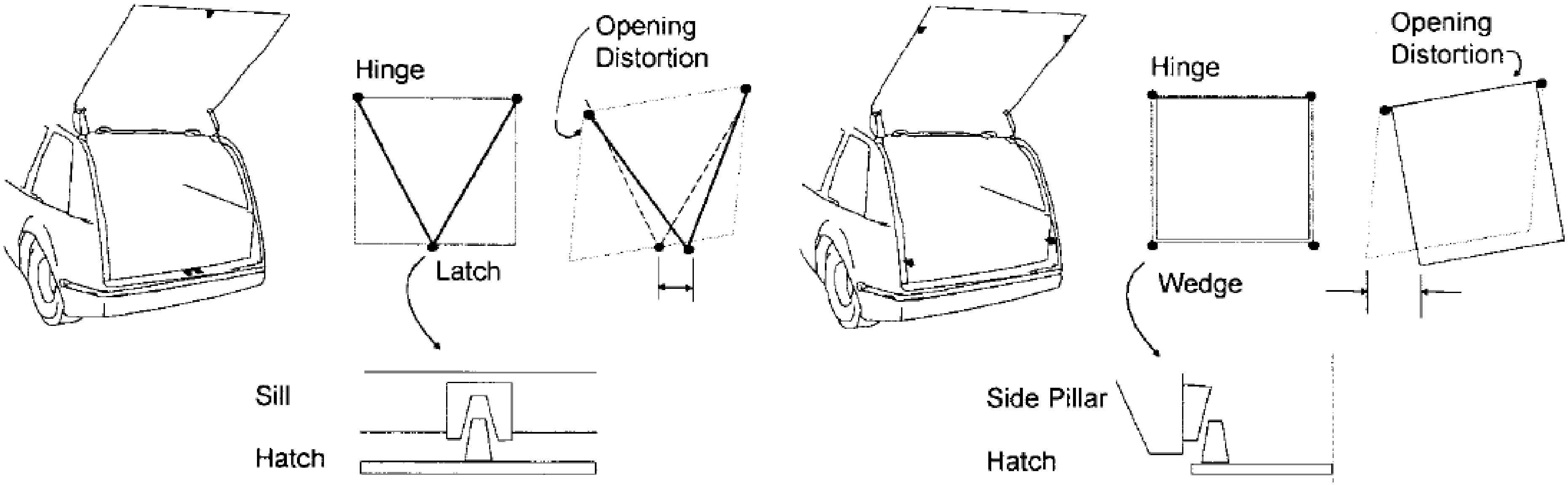
– Replace the rear panel with an open frame of rigid links with a typical joint stiffness
  - Typical joint stiffness: $K_j = 0.1\text{x}10^8$ Nm/rad
– Much more flexible frame than the original assumption of a flat panel

Example: Van Hatch Opening (2)

- $K = 1.6 \times 10^8$ Nm/rad = 2807 Nm/°
- Influence of the hatch opening: rear surface
  - Only one surface of the closed box need be flexible to reduce the stiffness for the whole box

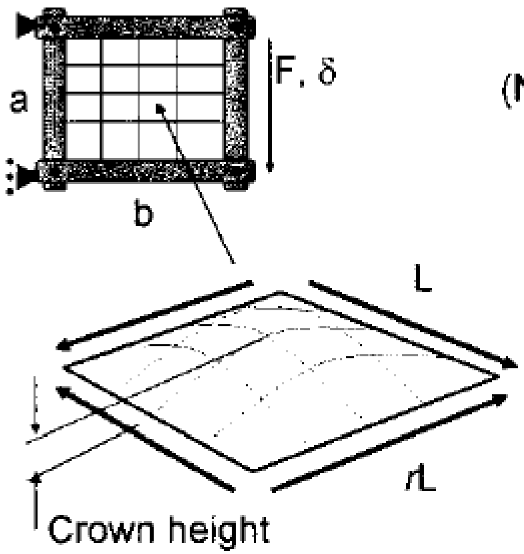
Example: Van Hatch Opening (3)

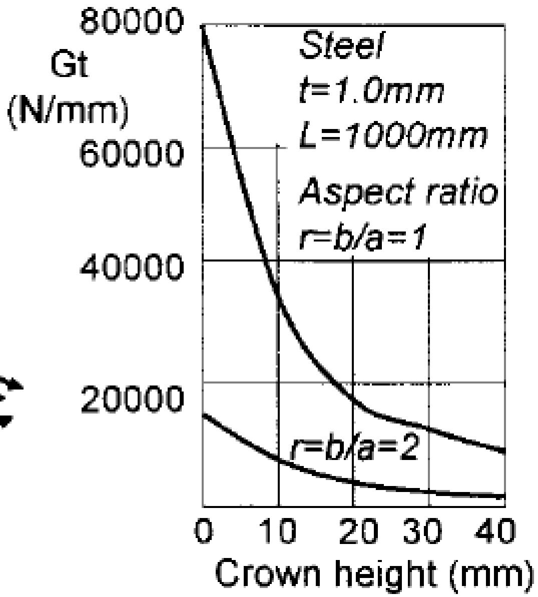
- In practice, increase the shear stiffness of the rear surface
- Typically the hinge and latch are not sufficiently stiff
- Mechanisms to wedge the door into the opening



Example: Crowned Panels

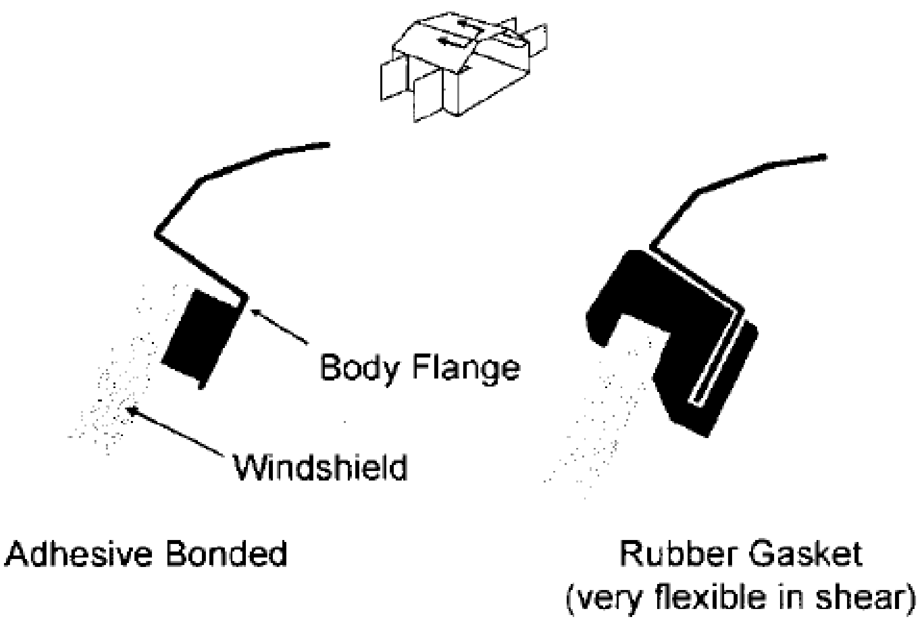
- Improve panel stiffness for normal loading such as dent resistance and panel vibration
- Effective shear stiffness?
  - FEA model of the shear test fixture
  - Much smaller than a flat panel (unrealistically high)



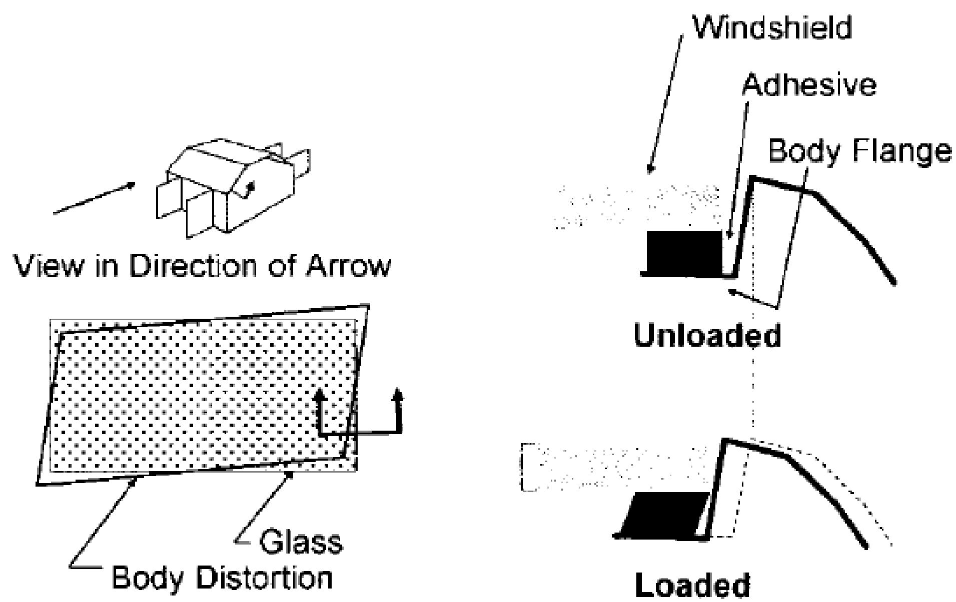


Example: Windshield (1)

- All surfaces enclosing the cabin must act as shear resistant members
- Most effective for shear resistance: adhesive bonding



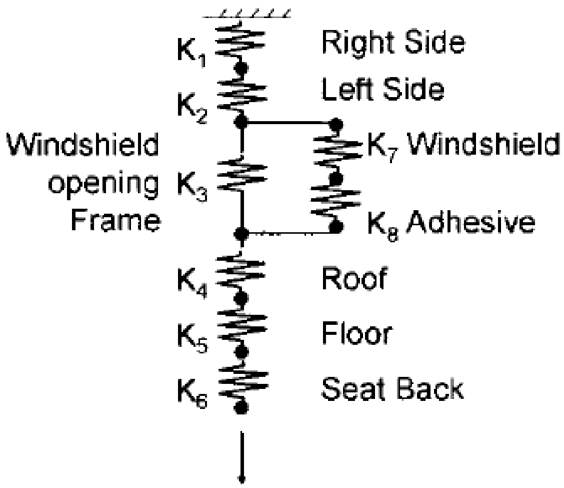
windshield retention alternatives



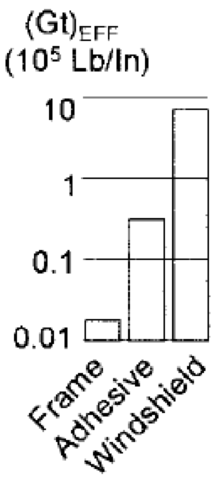
effective shear stiffness of windshield

Example: Windshield (2)

- Windshield model for torsional stiffness

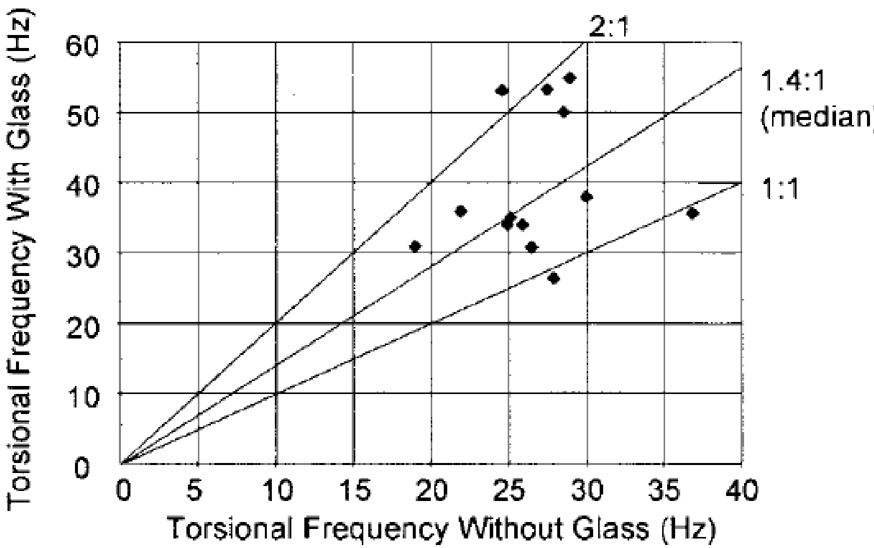


Spring Model of Windshield / Adhesive



Relative Shear Stiffness of Windshield Elements

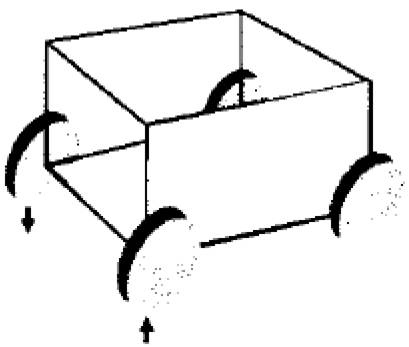
- Effect of windshield on torsional frequency
  - Increase with glass: torsionally stiffer body
  - No increase: very stiff body windshield opening perimeter



Example: Side Frame Model (1)

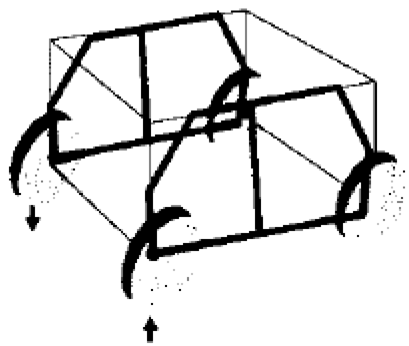
- Contribution to torsional stiffness
- Effective shear stiffness

Stiffness of Box with Panel Side

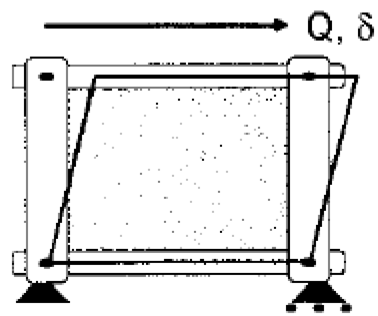


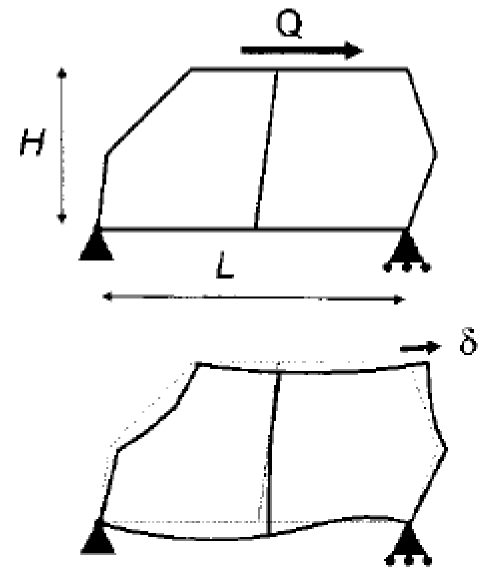
$$K_i = \left(\frac{Gt}{\text{Surface Area}} \right)$$

Stiffness of Box with Frame Side



$$K_i = \left(\frac{Gt_{Eff}}{\text{Surface Area}} \right)$$

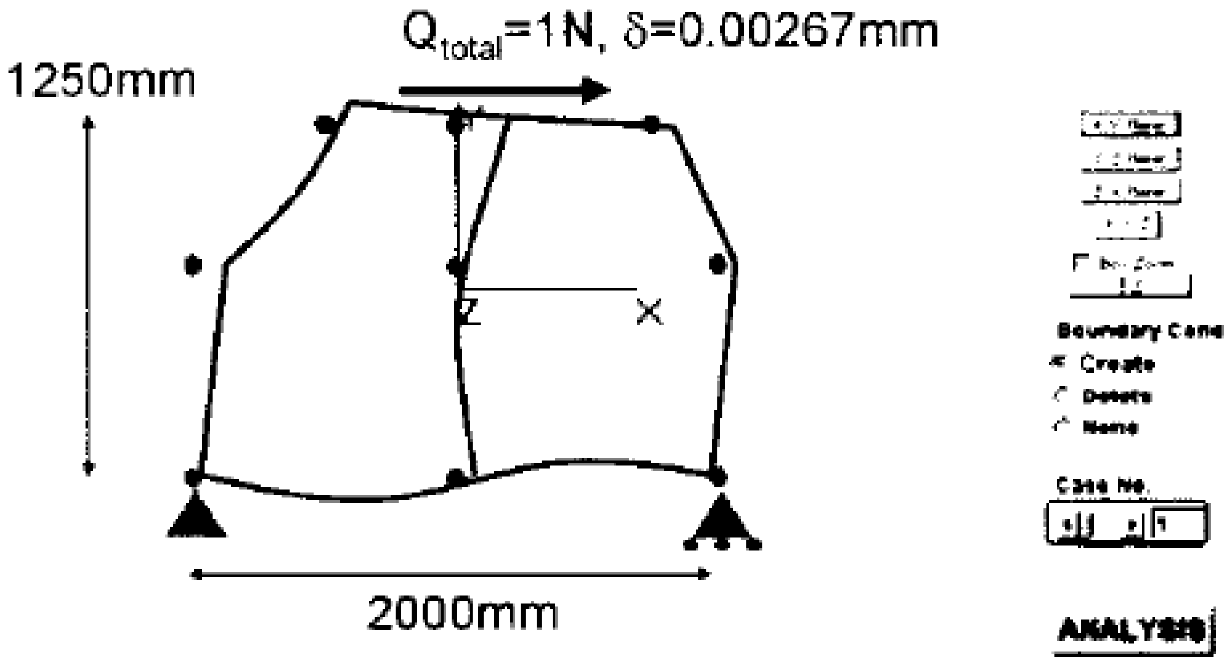




$$(Gt)_{eff} = \frac{Q}{\delta} \frac{H}{L}$$

Example: Side Frame Model (2)

- FEA under shear loading



$$(Gt)_{Eff} = \left(\frac{Q}{\delta}\right)\frac{H}{L} = \left(\frac{1N}{.00267mm}\right)\frac{1250mm}{2000mm} = 234N/mm$$

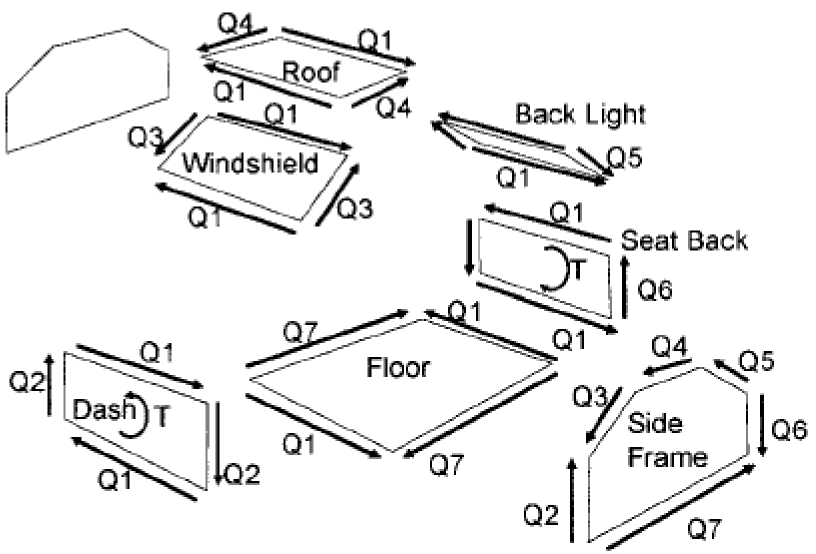
Torsional Stiffness of a Vehicle Cabin

- Solve for internal shear loads: $Q = A^{-1}T$
- Find the resulting shear flow on any non-loaded surface: q = Q/(side length)
- Determine the effective shear stiffness: $(Gt)_{eff}$
- Determine the torsional stiffness of the cabin: (q/T), $(Gt)_{eff}$, surface area

$$\frac{1}{2}T\theta = \sum_{\text{all surfaces}} \frac{1}{2} q^2 \left[\frac{ab}{(Gt)}\right]_i$$

$$\frac{\theta}{T} = \left(\frac{q}{T}\right)^2 \sum_{\text{all surfaces}} \left[\frac{\text{area of surface}}{(Gt)_{eff}}\right]_i$$

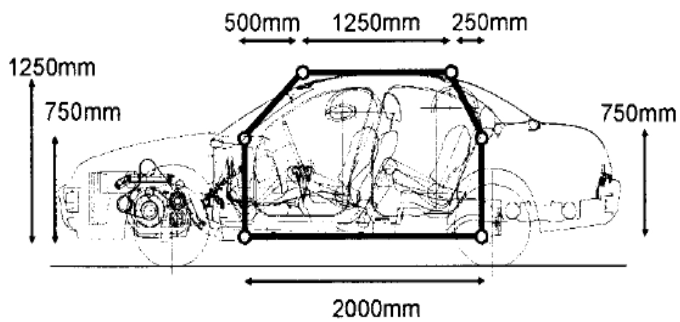
$$K = \frac{1}{\left(\frac{q}{T}\right)^2 \sum_{\text{all surfaces}} \left[\frac{\text{area of surface}}{(Gt)_{eff}}\right]_i}$$

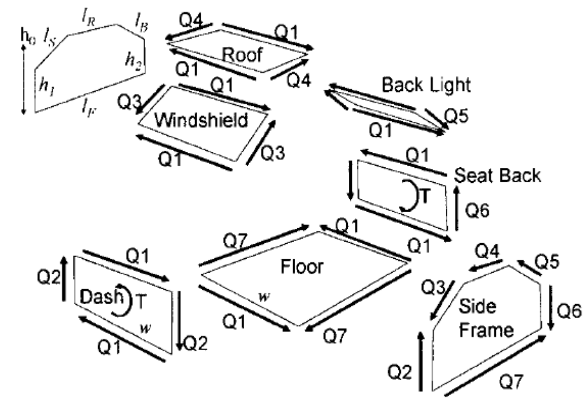


Cabin Surfaces

Example: Sedan

Torque	7730000
track	1560
h0	1250
h1	750
h2	750
Ls	707
Lr	1250
Lb	559
Lf	2000





A							T	Q	q
750	1560	0	0	0	0	0	7730000	3343	2.142758
707	0	−1560	0	0	0	0	0	3348	
1250	0	0	−1560	0	0	0	0	1515	2.142758
559	0	0	0	−1560	0	0	0	2678	2.142758
750	0	0	0	0	1560	0	7730000	1198	2.142758
2000	0	0	0	0	0	−1560	0	3348	
0	0	0	500	1789	−2000	750	0	4286	2.142758

panel	area	(Gt)eff	area/(Gt)eff
dash	1170000	80000	14.6
windshield	1103087	80000	13.8
roof	1950000	80000	24.4
back light	872067	80000	10.9
seat back	1170000	80000	14.6
floor	3120000	80000	39.0
side frame:L	2312500	234	9882.5
side frame:R	2312500	234	9882.5
SUM			19882.3

$$K = \frac{1}{\left(\frac{q}{T}\right)^2 \sum_{\text{all surfaces}} \left[\frac{\text{area of surface}}{(Gt)_{eff}}\right]_i}$$

$$= 6.55E+08 \text{Nmm/rad}$$

$$= 11{,}423 \text{Nm/}^\circ$$