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Sill and Tunnel Sizing For Frontal Crash

Automotive Chassis Systems

(ACHA5013)

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1.0 Introduction

This report will see the evolution of vehicle structures that have been a factor in the advancement of automotive engineering, directly influencing safety, performance, manufacturing processes, and design flexibility. In the early 20th century, as motor vehicles gained popularity due to the rise of gasoline-powered engines, initial vehicle frameworks were simple, consisting of separate body and chassis constructions. These early designs—typically open ladder chassis frames—offered limited torsional stiffness and structural integrity, often leading to excessive vibrations and poor performance over the applicable surfaces. However, as demand for faster vehicles, improved safety, and mass production grew, automotive engineers began experimenting with new materials, structural concepts, and integration techniques. This report explores the progression of vehicle structures from timber-and-fabric constructions to modern integral body designs, highlighting key innovations such as cruciform bracing, backbone structures, and triangulated tube frames. Each evolution represents a response to engineering limitations of time, paving the way for the high-strength, lightweight, and crash-resistant car bodies we see today.

2.0 The Initial Changes in Vehicle structures

Early indications of structural changes for vehicles started in the 1920's as demand for automotive vehicles started to rise with the recent introduction of gasoline. The standard orientation of the car became one where the chassis and body were treated as two units, this became favorable for companies as they were able to attach different bodies onto the chassis while maintaining the mechanical systems within the car.

A chassis would consist of an open ladder system where the frame would lay flat, with two hollow structural section (HSS) beams acting as the main frame, connecting the perpendicular beams running laterally across conjoined by rivets to the main beams. Open ladder system chassis frames are pliable locally in torsion but lack the ability to transfer bending moments into torsion and equally the transfer of torsion into a bending moment. The hinderance is mostly down to the rivetted joints within the chassis build, hence giving this chassis build low torsional stiffness making less than perfect terrain hard to maneuver as the transfer in bending moments was also lacking making the chassis undesirable and unreliable but as this was the early stages of engineering this was not recognized until later on.

As the chassis lacked torsional performance it benefited having the car body being minimalistic and lightweight as they were created with lighter materials such as timber which has a low stiffness. Furthermore, cars didn't encase the occupants fully with the body designs as most car had an open body design which only dealt with holding the occupants, payload and its own weight, as time eventually moved forward the car body was eventually experimented with by using metal clad bodies to improve the torsion stiffness, this came with some issues as the chassis and body were not one single attachment but two bodies the vehicle would experience 'rattling' and 'unnecessary vibrations' from the chassis now experiencing extra structural load from the increase in weight.



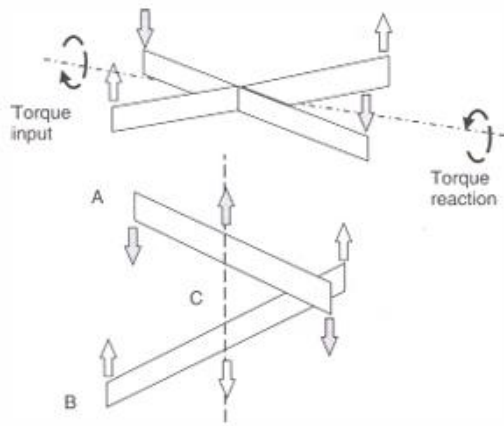
Book- Brown, J.C., Robertson, A.J. and Serpento, S.T., *Motor Vehicle Structures: Concepts and Fundamentals*. Cranfield University, UK: Butterworth-Heinemann.

(Figure 3.5 car body manufacture in the 1920s (Vauxhall Archive Centre))

To help with torsional stiffness a flexible body connected to a stiff chassis frame, this was created by using flexible metal joints between the body material and the chassis frame, this would decrease the vibrations that slightly but to further decrease the vibrations while keeping the torsional stiffness the car bodies become enclosed so that the torsion would be distributed more evenly throughout the structure. To keep the load on the chassis down the outer body was created by light weight material that is flexible, in Europe a fabric material was used and was instantly recognized as a viable option as it out done other options such as aluminum cladding which created unwanted stresses on key points of the wooden body frames, as vehicles become more viable the uses of them increased as more powerful and faster machines were needed, wooden frames with fabric become too weak to handle the current/further needs of the vehicles.

Moving from the 1920s to the 1930s the need for more robust design's cars moved from timber and fabric materials to steel pressed car body that have been made from steel sheets that were secured together with welding and riveted joints, this structure had much more torsional stiffness as the body was made to fit the chassis in hand the steel body increased the amount of shear the body can withstand while still maintaining a sperate body and chassis. To counteract the issue of 'vibrations' one of the approaches was to use flexible mountings in-between the body and chassis acting as torsion springs this created a 'load path' through the body softening the vibrations but decreases the overall stiffness as the body mountings are in parallel with the chassis the torsional load carried by the body is reduced.

The other approach that was taken was to use cruciform bracing which used cross-shaped brace added into the chassis frame were the ends need to be connected properly to the chassis in shear to the chassis framework,



Book- Brown, J.C., Robertson, A.J. and Serpento, S.T., *Motor Vehicle Structures: Concepts and Fundamentals*. Cranfield University, UK: Butterworth-Heinemann.

As the beam has a vertical load is applied at either end the load will then equally and opposite forces transferred at the intersects on the chassis frame, the bending and shear forces acting on the cruciform brace help the overall torsion carrying load of the structure. As engineering advanced the amount of torsion was taken into consideration at that time torsional stiffness values were between 1000 and 1750 Nm/deg for a magnitude of different chassis frames, the better cruciform-braced chassis frames would even reach over 2000 Nm/deg by adding smaller tie rods along the edge to minimize twisting and warping, this then became standard practice as small closed section cross-members made much more stiffer frames than that of open section frames.

Further into the 1930s it was found that entire steel- pressed bodies were much stiffer than the chassis in torsion and bending which allowed the body and chassis to share the moments more equally aiding the overall increase in stiffness. The method to conjoin the body and chassis was by incorporating screw holes within each of them. This would become some of the initial structural designs for modern vehicles of today. The additions of screws because the body and chassis are created from metal now, they can be welded together at the joints instead of riveting them which further enhanced the overall torsional stiffness.

The first type of steel-pressed car body that became popular was the integral body structure at the time due to its capability to be mass-produced and ability to self-support itself on the chassis, one of the main integral vehicle's structures in the 1930s was the Citroen 11 CV which was made in 1934 to 1958.



Book- Brown, J.C., Robertson, A.J. and Serpento, S.T., *Motor Vehicle Structures: Concepts and Fundamentals*. Cranfield University, UK: Butterworth-Heinemann.

(Citroen 11 CV of 1934 (courtesy of Automobiles Citroen SA))

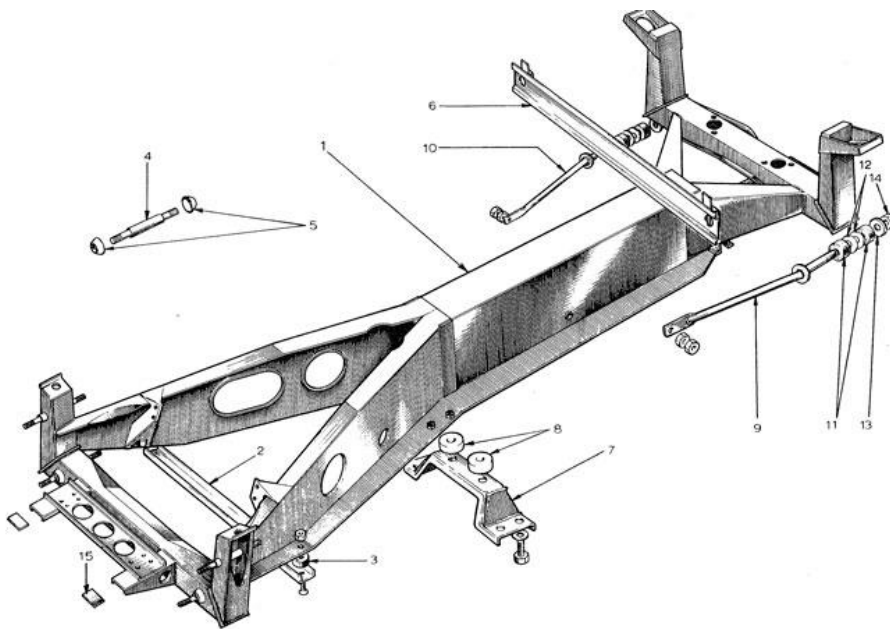
This car model was very similar throughout the years but a study by Swallow (1938) found that as the car body changed from the separate body-on-chassis in 1938 to the integral construction as the image above the torsional stiffness was tested between the two structures, the body of the 1938 model gave a value of 934 Nm/deg of torsional stiffness, the car model in 1939 which used the integral body structure gave a value of 3390 Nm/deg. This came down to several reasons, the main idea being that as the integral body having low slippage in-between the mounting bolts, allowing more torsional stiffness, which is shown in the study above.

3.0 Different Structure Types

The development of car structures varies throughout the years as new ideas were constantly being tested to try and get a better understanding of body stiffness, as bodies made by steel sheets become the normal, cars began to use large section tubes as this had more strength than thin sheets of steel but also being lighter than full rods some examples being,

3.1 Backbone Structure

The earliest chassis structure changes came from derivations of the older design Tatra vehicles, which had a 'backbone structure' from around 1930s. This structure now is used for specialist cars such as the Lotus Elan and Lotus Europa,



Lotus Elan- <https://lotusmarques.com/parts/catalogue/lotus/47-elan-2-parts/637-lotus-elan-2-chassis-components>

This structure is still a separate chassis frame, it achieves its high stiffness from its large steel sheet panels in the cross-sectional area through the middle of the chassis the panels are then in constant shear, this in turn leaves most of the shear loads on those panels but to decrease the total amount of shear on the backbone structure small triangular tubes are added to increase the total stiffness while not heavily increasing the weight of the structure.

3.2 Triangulated Tube Structure

This design builds the chassis and body as one with the triangulated structure encapsulates the body, in turn this creates a more rigid and stable framework that helps resist the twisting and bending of the structure, why triangles over squares (ladder), triangles have different attributes to squares as they cannot be deformed without changing the length of its sides whereas the quadrilateral shapes can collapse into parallelograms unless they are being supported by outside forces, this occurs as the forces on triangles hold their shape as they distribute forces more evenly along all vertices whereas squares do collapse.

Further, triangular tube's structures are effective at directing forces away from critical areas when the structure becomes overwhelmed such as a crash, the structure can absorb and dissipate the crash energy across the structure while minimizing the deformation of the vehicle in the passenger compartment, tube structures can crumple in a controlled manner acting as crumple zones absorbing the excessive forces and try to minimize the exposure to the occupant. Manufacturing this type of structure consumes a lot more time than simple pressing metal sheets as each tube will need to be welded to the frame/body of the vehicle so usually this structure is low production but cost effective compared to steel pressed sheets.

3.3 Birdcage Frame/ Modern Integral Body Structure

This structure is a more readily used modern structure that is widely known as birdcage frame. This type of structure uses small section tubular members that are incorporated into a main ring-beam frame by welding and rivet joints, ring-beam frames are effective at carrying local in-plane shear, this is due to the outskirts of the frame being very stiff to be able to stop the structure from bending as the edge members of the frame are the most susceptible to bending/braking. The main ring-beam is mostly made from steel whereas the smaller tube structures are made from aluminum, aluminum is an alternative metal to steel that has different uses such as being more malleable, so complex structure are easier to construct, further aluminum is 1/3 the weight of steel which reduces the overall vehicle weight. The birdcage frame on its own is not a very weight efficient shear structure but when skin panels are added the shear stiffness and torsional rigidity increases substantially, then the structure becomes an integral structure. As time goes on manufacturers had to also incorporate higher standards for safety to maximize occupant safety in a magnitude of situations such as high-speed crashes especially as car ownership has increased dramatically over the last few decades. To aid with this a new car standard was set to provide consumers with a safety performance assessment for the most popular cars in Europe, this was called the European New Car Assessment Program or more well known as the Euro NCAP, which was established in 1997. As new car structure was being created the manufacturers began to sponsor the testing of their own cars so that they can see improvements in their occupant star rating in the first couple

years of the Euro NCAP coming into fruition no car received a 5-star occupant rating, the first was a Renault Laguna in 2001. Following Renault's success most companies saw 5 stars as their main target for all new models of their vehicles.

As car manufacturers kept on moving forwards, new construction methods of car bodies were developed to keep up with the new needs for these vehicles. The ultralight steel auto body (ULSAB) is an alternative way of creating beam-like components this is done by forcing tubes into Moulds by using internal hydraulic pressure, to also increase the stiffness of the body spot welding would not hold on to its own, so laser welding and adhesive bonding are more extensively used as it results in stiffer and more light weight bodies compared to the standard ones. For example, the very best material to date for creating car bodies would be carbon fiber which is 5X stronger than steel while being $\frac{1}{4}$ the weight also as it's not a metal it does not rust, so why not use this for every car? The main reasons.

1. Expense- carbon fiber takes a lot of energy and labor to create as it's not able to be machine stamped but either by hand or molded, the materials and resin become costly as so much material is needed to create a car body.
2. Repairability- carbon fiber when broken does not dent or bend rather cracks and shatters and once the structure is broken it loses all its strength, the cracks are not readily visible as carbon is dark/black and repairing carbon is not possible in most cases meaning a whole new body would need to be made to replace it.

4.0 Conclusion

The transformation of vehicle structures over the past century demonstrates the automotive industry's constant pursuit of performance, safety, and efficiency. From the rudimentary open ladder chassis of the 1920s to the highly engineered birdcage and integral structures of today, each development has introduced new materials, techniques, and design philosophies. Improvements in torsional stiffness, weight distribution, and crash performance have been driven by both practical challenges and evolving consumer expectations. Innovations such as cruciform bracing, backbone designs, and the strategic use of lightweight materials like aluminum and carbon fiber have redefined what is possible in automotive construction. While cutting-edge materials like carbon fiber offer exceptional benefits, limitations in cost and repairability restrict their widespread use. Nonetheless, ongoing advancements such as ultralight steel auto bodies and precision welding techniques continue to shape the future of vehicle design. The legacy of these structural changes is evident in modern vehicles that are safer, more efficient, and more adaptable than ever before, reflecting a century of engineering progress rooted in structural innovation.

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