Formula SAE
A Guide to Meeting the Structure Equivalency Requirements for 2008

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Introduction

The Formula SAE rules outline the minimum required structure of all vehicles wishing to compete. The Structure Equivalency (SE) process is intended as a way to give the schools design freedom as well as explore different fabrication methods, such as composite monocoques.

This document does not supersede the rules in any way and where a conflict exists between this paper and the rules, the rules prevail and must be followed. Additionally, this is not meant to encapsulate or summarize the rules, simply answer questions and provide assistance in proving structural equivalency.

The rules state "The teams must submit calculations for the material they have chosen, demonstrating equivalence to the minimum requirements found in Section 3.3.3.1 for yield and ultimate strengths in bending, buckling and tension, for buckling modulus and for energy dissipation." This rule is indicating that to achieve structural equivalency a design must be shown to be equivalent in every possible loading scenario that the structure could be expected to see in normal operation.

Monocoque Overview

A monocoque construction requires the most amount of work for a Structure Equivalency (SE). This is true whether the monocoque be composite or metallic. Your task will be to convince the technical reviewers that your design is equivalent or better than a steel tubular chassis of the same basic geometry.

If you are using a composite monocoque the SEF process becomes more involved. You may have to use either laminate theory and/or finite element analysis to show that your design is equivalent in strength and energy dissipation regardless of where the external object strikes the car. In either case, it is never sufficient to show one load case and explain this is the worst – you must prove which case is the worst and that your structure is completely equivalent or better.

Tubing Substitution

Many of the SE submissions received concern substituting different sized tubing for roll hoops, bracing and side impact tubes. For example, consider the side impact tubes. In a side impact the side impact tubes isolate the driver from the impacting object, and dissipate the energy of the collision. This means that a side impact structure must be shown to have the same strength as the three steel tube design outlined in the rules, as well as energy absorption. If you are simply replacing the tubes with larger diameter and stronger alloy steels, it becomes quite easy to show that in all scenarios the new design is superior. Calculating the cross sectional areas and moments of inertia and comparing them back to the baseline tubes effectively accomplishes this, with supporting explanation of your thought process.

The SE Form – Line by Line

The following excerpt is taken from the SE form and shows how the major structures of the car are broken down. Please always include a fully filled out SE form with your submission. There is also an additional column for you to summarize your design such as "1.00"x0.049" square tube with ¼" hole." This will assist the scrutineers at Technical Inspection.

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We will now examine each item in more detail.

3.3.4.2 Main Roll Hoop

Because main roll hoops must be steel, most equivalencies will concern the diameter and wall thickness. Make sure your design does not fall below the minimum wall thickness given in the rules (3.3.3.2.2 Steel Tubing Requirements), and has sufficient area, modulus and material properties. Remember, your main roll hoop and front roll hoop must have an exposed portion with inspection holes for determining diameter and wall thickness.

3.3.4.2 Main Roll Hoop Attachment to Monocoque

Proving equivalency of the main roll hoop attachment can be trickier than showing equivalency of the roll hoop itself. Rule 3.3.4.2 states that the main roll hoop must be attached with an adequate number of 8mm bolts and 2mm thick (backing) plates. Use of adhesive as additional structural transfer is acceptable, but we want to ensure that the main roll hoop is structurally attached with mechanical fasteners that we can verify at Technical Inspection. The quantity, location and design details of the main hoop attachment, including drawings, must be provided with supporting calculations.

3.3.4.3 Front Roll Hoop

Composites are not allowed for Front Roll Hoops. They must be closed section metal tubing, and must be connected securely to your monocoque. Closed section includes round, near round, box and other tubing shapes that form a closed cross section. Make sure your design does not fall below the minimum wall thickness given in the rules (3.3.3.2 Alternative Tubing and Material), and has sufficient area, modulus and material properties.

Unlike the Main Hoop, Rule 3.3.4.2 does not govern the front roll hoop attachment. Use of adhesives is acceptable, if the hoop is completely contained in composite and the ply material and adhesives are demonstrated to have sufficient strength. The design details of the main hoop attachment, including drawings, must be provided with supporting calculations.

Remember, your main roll hoop and front roll hoop must have an exposed portion with inspection holes for determining diameter and wall thickness.

3.3.5.1 Main Roll Hoop Bracing

The rules dictate a steel closed-section main roll hoop bracing. Additionally, provide detailed information on the manner of the bracing attachment. If the bracing is welded into the structure at both ends it is not considered mechanically attached. The bracing is considered mechanically attached if fasteners are used at one or both ends, regardless if the team has any intention of disconnecting the attachment while at the competition. Section 3.3.5.5 (Mechanically Attached Roll Hoop Bracing) should be referenced which outlines acceptable methods of fastening to a space frame.

New in 2008 is the following phrase near the end of 3.3.5.1:

> "Bracing loads must not be fed solely into the engine, transmission or differential, i.e. the bracing must terminate at a node where there is a load path through the Primary Structure."

The basic test that will be applied for 2008 and beyond for the Main Hoop Bracing is that with the engine and transmission removed, there must be a load path, made from approved sized steel tubing, from the bottom of the Main Hoop Bracing back to the Main Hoop. The minimum dimensions of approved steel tubing are 1.00" OD x 0.049" wall. Preferably it would be 1.00" OD x 0.065" wall.

If you want to use part of a Powertrain component (such as a homemade differential casing) anywhere in the load path you will need to show equivalency with that component and all interconnecting components back to the main roll hoop. You have to show equivalency against the 1.00" OD x 0.049" steel tube that is required.

If attaching to a monocoque, please see section 3.3.5.3 as all Main Hoop to monocoque attachments are by definition Mechanically Attached.

3.3.5.2 Front Roll Hoop Bracing

Front roll hoop bracing can be metallic tubing. The composite monocoque may also serve as the front roll hoop bracing. Provide standard composite information. The bracing must form a continuous load path from the roll hoop to the major structure of the chassis. The rules say the bracing should extend to structure in front of the drivers feet, which does not mean it is mandatory.

3.3.5.3 Monocoque Bracing Attachment

When the bracing attaches to a monocoque, there are additional design cases to consider. First, the mounting plates and backup plates should be sized to prevent all the possible failure modes at the interface, such as perimeter shear of the laminate or bolt failure, to name two. The quantity and design details of the fasteners and backing plates should be given, along with supporting calculations and drawings of the installation. Backing plates that were incorrectly sized have been submitted in the past, and the teams were required to increase the surface area until the shear loads in the monocoque were sufficiently low. A good rule is to ensure the bracing tube will fail by any of the possible failure modes (tension/compression, buckling, etc.), before the attachment point. This is equivalent to a professionally welded space frame where the tubes will rarely fail at the weld, but rather in the tube some distance from the weld.

The section on 3.3.5.1 covered a new rule for 2008 that mandates a load path from the main hoop attachment back to the main roll hoop. On a composite car this could be entirely a steel space frame bolted to the tub or part of this load path could be the monocoque itself. Regardless you will need to include in your submission an explanation of the design connecting the main hoop bracing to the main hoop and calculations showing equivalency to the required 1.00" OD x 0.049" steel tube. On some cars this load path might even be through a differential case, steel tube and then part of the monocoque, but all elements making up the load path and their interconnection must be demonstrated to be equivalent.

3.3.6.1 Front Bulkhead

For tubular front bulkheads where diameter or wall thickness are being varied equivalency can be shown by comparing section areas, moments of inertia and material properties of the design outlined in the rules and the new proposed design.

3.3.6.1 Monocoque Front Bulkhead

The primary loads acting on the front bulkhead are frontal impact, or possibly roll over depending on the frame geometry (height of front roll hoop relative to main hoop). Provide documentation of the strength of the front bulkhead relative the design outlined in the rules.

Include additional information relevant to the monocoque, such as rivet size and spacing for aluminum panels or composite lay-up technique, material used (cloth type, weight, resin type, number of layers, core material, and skin material), if composite. Additionally, explain your failure criterion (such as Tsai-Wu), and why it is the appropriate criterion for your design and how your design is equivalent in all ways to the standard steel design. Make sure to check the worst point(s) of the structure, which will normally be at the center of the bulkhead but may not be due to laminate variations or internal bracing. You can use any one or combination of analysis techniques, such as classical laminate theory or finite element. Whichever you pick, make sure it is well documented and appropriate to the load case you are studying. Since you are trying to show the performance of your design relative to the base, the exact magnitude of the assumed load is not important.

3.3.6.2 Front Bulkhead Support

For tubular front bulkhead supports where diameter or wall thickness are being varied equivalency can be shown by comparing section areas, moments of inertia and material properties of the design outlined in the rules and the new proposed design. Many teams machine cutouts in the front bulkhead support tubes for mounting of the suspension links. These cutouts are allowed. However, when showing equivalency calculations must be presented that show the tubes are equivalent to the baseline steel material at the cutouts. The use of gussets and reinforcing material is allowed and encouraged where needed around the suspension cutouts. As stated in section 3.3.6.2 all tubes comprising the bulkhead support must meet the minimum and equivalency must be sought for any and all tubes that deviate from the minimum specified in the rules.

The rules require node-to-node triangulation with at least one diagonal brace on either side. In essence, it is necessary to have the front bulkhead supported by a triangulated structure. This may be comprised of one diagonal tube from the bulkhead to a structural node to the rear, or a series of tubes so long as a truss-like structure is formed. If there are any doubts about whether a specific configuration meets the rules it is suggested a drawing be included with the SEF submission or a rules clarification submitted.

3.3.6.3 Impact Attenuator Attachment (& Anti-Intrusion Plate)

The attachment method of the Impact Attenuator (IA) is now called out explicitly as being either welded or attached with a specific number and quality of fasteners. If alternative fastening methods are used (such as camlock fasteners, six bolts, etc) equivalency will have to be shown to the fasteners called out in the rules. Also, for certain designs of attenuators a backing plate or Anti-Intrusion Plate (AIP) is now required. This plate can sit sandwiched between the IA and the front bulkhead or be completely integrated into the IA, but it must be secured with the fasteners (or the processes shown to have equivalency) called out in the rules.

Your Anti-Intrusion Plate can be of a different design but you will have to show it is equivalent to the AIP in the rule. If made of composite please see the composites section under “General” near the end of the document for additional guidelines.

3.3.8.1 Side Impact Protection Material

A simple way to show equivalency for metallic tubular side impact structures is to use section properties for the complete Side Impact Protection system. Remember that moment of inertia and area are both required. Do a comparison to three steel tubes at the same span between your Roll Hoops. Some teams have also done testing on sample sections to verify and/or determine the structure strength. Make sure to check any questionable locations of the structure where peak stresses could occur. Normally the worst location is midspan of the longest tube. For simple geometries hand calculations should be sufficient. For more complex geometry, finite element analysis might be required. If the side impact structure is attached to the vehicle, such as the case of a composite sandwich panel attached to a steel space frame, you must also show the attachment method is stronger than the crush strength of the impact structure. This attachment strength is critical and requires proof with your submission, especially when using composite panels attached to a steel space frame.

3.3.8.2 Composite Monocoque Side Impact Protection

Same as 3.3.8, but include additional information relevant to the composites, such as the composite lay-up technique, material used (cloth type, weight, resin type, number of layers, core material, and skin material). Additionally, explain your failure criterion (such as Tsai-Wu), and why it is the appropriate criterion for your design and how your design is equivalent in all ways to the standard steel design. Make sure to check the worst point(s) of the structure, which will normally be at midspan but may not be, especially for composite tubs with varying layup thickness or ply orientation. You can use any one or combination of analysis techniques, such as classical laminate theory or finite element. Whichever you pick, make sure it is well documented and appropriate to the load case you are studying. Since you are trying to show the performance of your design relative to the base, the exact magnitude of the assumed load is not important. As mentioned in section 3.3.8 if the impact structure is not integral to the chassis (part of the tub layup, etc), then the attachment method is critical and proof of equivalency must be part of the submission.

3.3.8.3 Metal Monocoque Composite Side Impact Protection

Same as 3.3.8.2.

3.4.1 Monocoque Safety Harness Attachment

The attachment of safety harnesses to a monocoque, as well as space frames, is probably the number one problem seen with structural equivalency submissions. The lap belts should be mounted on pivots, such that the angle of the belt over the hips can change with different driver size or seat position. "U-type" bars, with an attachment point at both sides and the belt in the middle are good choices for the shoulder belts in a monocoque, but not for the lap belts. Most teams underestimate the loads involved in a collision. Even an FSAE car traveling at the low speeds seen in the competition can put significant loads through the harness and structure in the event of a collision. The harnesses must be attached to the major structure of the vehicle, and every part shown to be sufficient for a crash. If you are unsure where to start in sizing the attachments points of your safety harness, carefully examine the components supplied by the manufacture. Consider the loads they are designed to carry, and aim to make your structure equally strong. Documentation available on the web for one harness manufacturer shows belt tensile strengths to range from 5,000 lbs all the way to 15,000 lbs, depending on the material purchased. Also, think about the seating position of your driver and what the loads going through the harness are in high deceleration events. A free body diagram can help. There is no recommended deceleration rate to use for showing equivalency, but whatever rate you use show justification and that your design can withstand it.

Other General Information

Diagrams: Diagrams of your design are necessary for us to understand it fully and can include neat hand sketches, engineering drawings, images of CAD solid models, or pictures of physical hardware - whatever convey the design most clearly. In most cases you will need to include key dimensions, such as the span on your side impact tubes, which will be used in your calculations.

Experiments: Experiments are normally a very convincing way to show equivalency. Some times a design is very complicated and a test can readily show the strength or energy absorbance of a component. Pictures of experimental setup are very helpful, as are simple diagrams showing the fixture. If you are going to present experimental data, it is normally best to also test the base structure. This will normally involve welding up some steel tubes and testing them when you test your new structure. It is hard to compare calculations to experimental results for complicated systems but if the system is quite simple it may be sufficiently accurate to compare experimental and calculated values.

Calculations: Scanned pages of hand calculations are perfectly acceptable. Likewise, calculations done in a word processing package are fine. Please show your work clearly, defining variables and show a logical workflow.

Finite Element Analysis: FEA can be a very useful tool for showing equivalency between your proposed design and base. To grant equivalency we have to understand your methodology. Methodology includes, among other things:

1. Type of analysis: Linear static, non-Linear static, non-linear dynamic, etc.
2. Element Type and Order: 4 node Tetrahedron, 10 node tetrahedron, shear panel, etc.
3. Laminate definitions: Layup regions, laminate, ply thickness and orientation, etc.
4. Boundary conditions: Loads, displacement constraints, rigid elements, etc.
5. Failure criteria: Von Mises,Tsai-Wu (Composite), etc.
6. Other modeling variables: For example, for a dynamic crash analysis, what is the mass of the vehicle, initial velocity, etc?

And lastly, support the decisions you have made by explaining why each one is appropriate. You will undoubtedly make assumptions, but explain what led you to that assumption.

Composites: Composite monocoques are probably the most difficult structure to prove equivalency on, but thoroughness and attention to detail can make these structures very safe. Lots of graphics will assist us in understanding the basic geometry, as well as the detail design points, such as main roll hoop and bracing attachment methods. Make sure you outline all the details of the layup itself, such as layup regions, laminate, ply thickness and orientation. When you specify your ply orientations, be sure to include your zero reference. Include all material properties from the manufacturers for both the fiber and resin systems, as well as whom the manufacturer is, the trade name of the material, etc. Process is critical to composites construction, and we need to understand what process you are using, and that the materials you have picked are appropriate to that process. It is very useful to build smaller specimens and test them to verify that your process is giving equivalent mechanical properties to the ones quoted by the manufacturer. This is especially important if you have modified or are using a different process altogether than for what the material was designed. Just like the FEA section above stated, make sure that after you calculate stresses you use a failure criterion correct for your situation and check all the plies in the laminate.

A critical area of composite design and manufacture is where the monocoque attaches to other structures, whether these are the roll hoops and other structure, seat belt attachment points or even suspension links. The structural equivalency process is concerned with how many but not all of the components attach to the monocoque, but you will need to design effective joints at every attachment point. When attaching the roll hoop the rules state that 8mm bolts will be used and 2mm steel plates, both sides.

One last thing to consider for composites are the many different failure modes that can occur. When demonstrating equivalency, the weakest failure mode is the one that matters, so be sure to consider them all. This is especially true at inserts and hard points. Details of these should be given, and section drawings showing the core and skins with insert are very helpful in understanding the design.

One potentially useful website covering some failure modes for sandwich structures is: http://www.hexcelcomposites.com/Markets/Products/Honeycomb/Sand_design_tech/default.htm

Seat Belt Attachment: As stated earlier in the monocoque safety attachment section, the two lap belts should attach to the monocoque in such a way to allow them to self align with the force at the pivot. These would be the bolt-in or snap-hook style shown below.

It is important to make sure on the bolt-in design that the belt is still free to pivot and the bolt does not place clamp load through the seat belt tab. The snap-hook type is designed to be used with an eye bolt. The wrap around style seat belts can be used for the shoulder belts and anti-submarine belt(s). The bolt-in style can also be used for anti-submarine belt(s). The cross tube that the shoulder belts mount to is considered part of the primary structure structure, and must comply with rule 3.3.3.1, giving a minimum tube of 1.0"x0.095". The other seat belts, such as lap or anti submarine, can be attached to 1.0"x0.065" tubing.

Conclusion

The major cause for teams having difficulties at Technical Inspection is that they failed to highlight in their structural equivalency submission that they had deviated from the rules. When in doubt – check. If your composite monocoque passes the equivalency process, but you failed to indicate you had removable roll hoop bracing that deviated from the rules, then tech will go slowly and it is likely you will have to make changes at the competition. You should include as much documentation as you can, in whatever format is most clear. But the important thing to remember is we can only approve what we have seen.

Submit your SE form early – before you start to fabricate and while you still have design flexibility. That way you can incorporate any changes early in the process and avoid tearing up the vehicle.

Finally, bring your approved SE form and all supporting documentation to the technical inspection at the competition. This will assist the technical inspectors with approving your car to compete.