

Design and Development of an Integrated Firewall-Seat for Formula SAE Car

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Abstract

Purdue Northwest Formula Society of Automotive Engineering (FSAE) team was founded in the 2015-2016 school year and has been at the forefront of undergraduate student research in the engineering disciplines as well as community outreach. It has provided students an accessible and realistic insight into how the knowledge that they learn in the classroom to be applied to scenarios within the workforce and in future academic settings. Design and Development of an Integrated Firewall-Seat for Formula SAE Car has allowed student researchers to gain a fundamental working knowledge of vehicle engineering, the Engineering V, mechanical design and optimization, applied mechanics, thermodynamics, materials, manufacturing techniques, and static/dynamic force analysis through finite element analysis (FEA). All accomplishments were completed within a summer of preliminary research, and prior to applying these concepts in the classroom and to the 2020 vehicle components.

Introduction

Formula Society of Automotive Engineering (FSAE) is a student organization that designs, builds and competes an open-wheeled formula style race car annually at Michigan International Speedway. The team at Purdue University Northwest, entering its fifth season with its fifth consecutive build, has gone to competition for four consecutive seasons and twice completed the final endurance event. In the 2018-2019 season, many safety and manufacturing improvements were made to systems relating to driver safety and comfort as well as weight reduction on the vehicle. The only exceptions were the seat and firewall having been left as afterthoughts for all four completed seasons. This will be the first complete design and material overhaul of both components in the team history, allowing the Purdue University Northwest FSAE team to begin making similar design and safety improvements to its top competitors. It has been noted by many top teams that structural components such as the firewall are comprised entirely of composites. This paper examines the design, research, and development phases of the firewall- seat component for the PNW FSAE car. This is one of many projects to be completed in the 2019-2020 season by students. These projects give students the opportunity to learn, develop, and apply skill sets crucial to the engineering field prior to learning them in the classroom. In addition, it will prepare them to enter the workforce directly out of college and allow them unmatched exposure to potential employers at the FSAE design events. Design and Development of an Integrated Firewall-Seat for Formula SAE car has allowed student researchers to gain a fundamental working knowledge of vehicle engineering, the engineering V, design optimization, applied mechanics, thermodynamics, material sciences, manufacturing, and static/dynamic force analysis through finite element analysis (FEA). Students are responsible for all aspects of the design and development of the FSAE car from the conceptualization to financial aspects of the build and manufacturing.

Methodology

Beyond Engineering

Beyond the engineering realm, members of the Purdue Northwest Formula Society of Automotive Engineering Team volunteer in community outreach efforts on and off-campus. On-campus FSAE participates in several events to benefit students of all majors and educational experience levels such as the annual Enbridge Summer Engineering Camp, Welcome Week, and college preview events. Off-campus they are actively involved in STEM on the Road, a school run outreach program where students from the team travel to local high schools and bringing the car into their world. Aside from STEM on the Road, members of all majors involved in the team frequently travel to local high schools on recruiting trips with university advisors.

The Engineering V

In order to successfully manage and complete a project, engineers must first define it, which includes isolating the problem, a skillset commonly taught in rudimentary engineering classes [26]. They must also have the ability to formulate a well-founded hypothesis of a plausible solution. The next phases of the project fall under project management, which include: implementing the solution, testing, prototyping, manufacturing and maintenance.

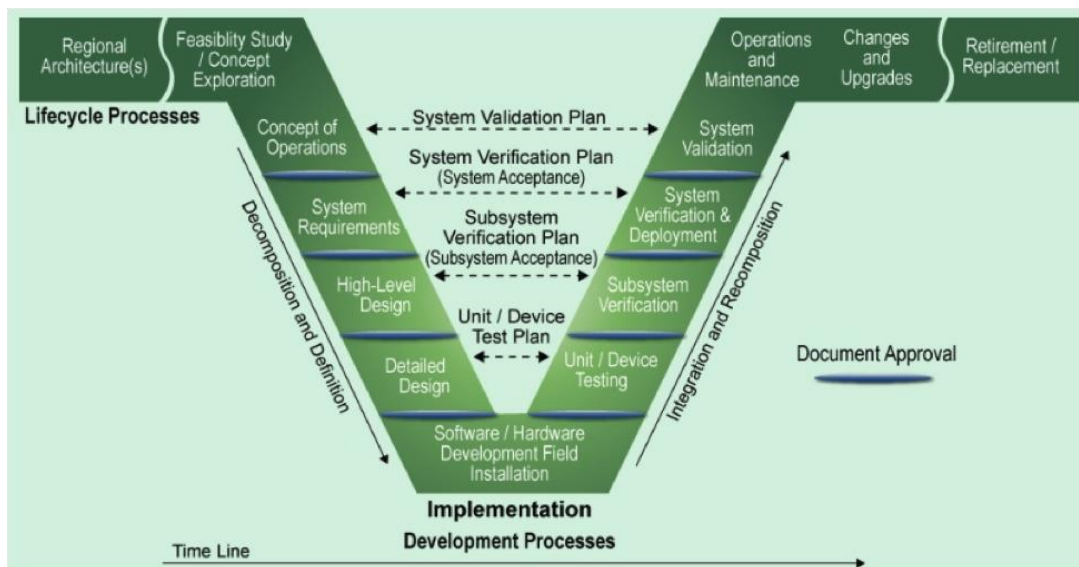


Figure 1: The Engineering V [26]

According to the Engineering V under the concepts of operation heading, a well-founded hypothesis includes a foundational understanding of design requirements and restrictions. This is shown by the hypothesis and component definition in the following which are being used by the 2019-2020 FSAE Firewall and Seat redesign team:

Defining the firewall:

The firewall is the component of a Formula 1 or FSAE car that protects the driver from components of the control system and engines, such as the electrical wiring harness, fuel tank, exposed areas of the engine, and acts as an explosion and fire shield.

Hypothesis:

In order to have the optimal racing seat and cockpit design configuration that reduces weight, increases driver stability, and improves safety, it is necessary to look at the combined seat and firewall. This should be accomplished by changing the current multi-piece seat and firewall into one cohesive system. The present disjointed weight restrictive system should be changed to a cohesive carbon fiber base, Kevlar core firewall with an aluminum shield, accompanied by cost-effective foam inserts to serve as the seat. This design will increase the driver's comfort and safety while reducing the weight of the vehicle.

Implementing the solution

In the process of implementing any type of solution, engineers must take into consideration the rules that govern the organization affiliated with the project, a commonly stressed point among all professors of classes relating to design and project management. They must also take into consideration the analysis needed to be run to ensure the component safety, cost, material integrity, and ability to manufacture. FSAE implements a stringent rulebook governing all aspects of each vehicle. Below are a few considerations that the FSAE students have taken into account during the 2019-2020 FSAE Firewall rebuild.

According to the rules from the FSAE 2019 rule book regarding the restraining harness [9]:

- The lap belts must pass around the pelvic area below the hip bones.
- They must pass through the seat at the bottom and sides and continue in a straight line to the anchorage point.
- The seat must be rolled or have grommets in areas where the harness passes through holes in the seat.

According to the rules from the FSAE 2019 rule book regarding the seat [9]:

- The driver's seat must be protected by either having the lowest point on the driver's seat no lower than the bottom surface of the lower frame rails, or a longitudinal tube(s) that meets the side impact tubing requirements passing under the lowest point of the seat.
- There must be heat resistant, conduction isolation material with a minimum thickness of 8 mm between a source of heat and the driver of a 25 mm air gap.
- Radiation isolation must be done with a metal heat shield or a reflective tape when combined with insulation material.

According to the rules from the FSAE 2019 rule book regarding the firewall [9]:

- Be made of a non-permeable surface made from fire-resistant material.

- Seal completely against the passage of fluids (the firewall itself, and the edges where it contacts the chassis)
- The restraining harness must not pass through the firewall.

In addition, the top of each driver's helmet must be 50 mm below the tangent line between the center node on the nose cone and the roll bar. It is illustrated below (Figures 2.a and 2.b) in a graphic from the FSAE rule book [9] and shown by a photo taken of the 2019 car at the tech inspection.

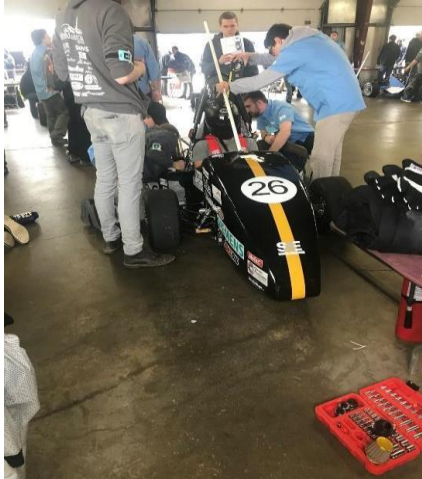
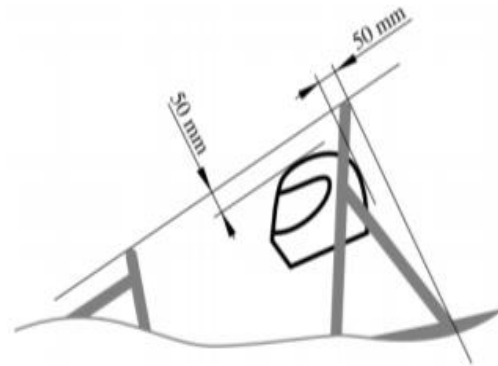


Figure 2: (a) FSAE Tech inspection



(b) Nodal distance to helmet [9]

Design Optimization

Two of the most crucial factors in any design and manufacturing process are design intent and design optimization. In order to be able to compete against the top teams in FSAE competition, the team must begin to ensure that all areas of the vehicle are comprised entirely of purposeful geometry that has been tested extensively and documented. Therefore, to ensure that all steps of the process can be accounted for, they must have the ability to learn from past designs, mistakes, and successes in order to consistently improve all vehicle systems.

According to members of the 2019 FSAE competition team, one of the most pressing issues with the design of the firewall was its inability to be easily removed. To make the components protected by the firewall easily accessible, solutions such as adding a metal hinge(s) to the base of the firewall where the chassis narrows have been considered. Adding the hinge(s) would leave a small gap that can be sealed with a heat resistant electrical tape.

Student researchers created a detailed design in SolidWorks. The preliminary design concept failed during the Finite Element Analysis process, after attempting to use linear corners as attachment points to the rounded steel pipe frame of the chassis. This caused high amounts of stress and strain at the attachment points. The final design follows the rounded 0.5 inch radius of the space frame chassis at all attachment points and corners. Rounding the edges allowed forces to be distributed evenly throughout the object, while maintaining the same uniform thickness throughout the part of 0.0625 inches. Figure 3 illustrates three views of the final design via a CAD

Drawing created on SolidWorks.

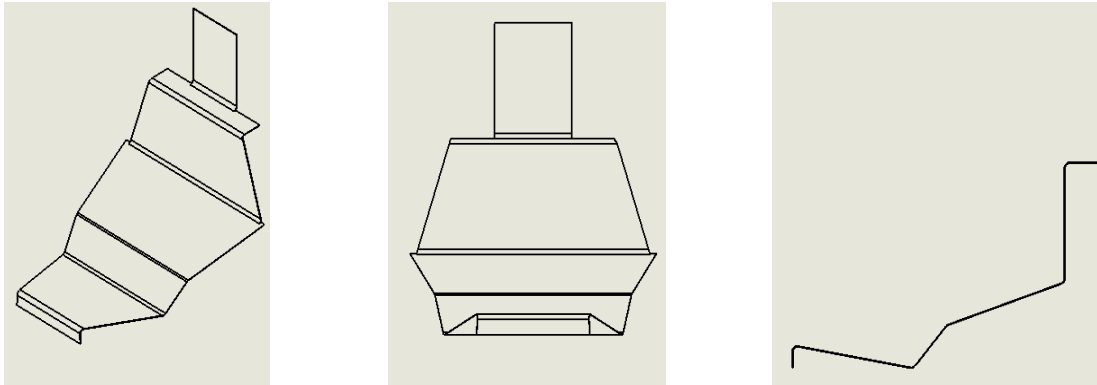


Figure 3: (a) Isometric view

(b) Front View

(c) Side view

Design Factors

The customized foam inserts atop of a composite firewall gives greater driver stability when facing turns at high speeds. In addition, it eliminates the fluctuation of forces on the chassis and suspension, particularly on sharp turns and in tilt at large angles. These cost-effective, lightweight custom inserts will allow more variance in driver height.

Material Analysis

In order to achieve research goals and the safest possible outcome for the driver, material properties were closely analyzed. The material properties analyzed were the ultimate tensile strength (UTS), strain, heat rate, and R-value. Stress is defined as the applied force per unit area [16]. Stress may or may not be uniform and is measured in Pascal (Pa) or Newtons per square meter [16]. Strain is defined by the elongation divided by the original length, measured in meters per meter [16]. Heat rate measures how well an object resists heat flow; it is measured in units K/W [22]. R-value is the thermal insulation factor, which measures resistance to heat transfer; it is measured in $[m^2 (K)]/W$ [22]. The above are explained in the equations below.

$$\text{Tensile Stress} = \frac{F_{\perp}}{A} \quad (1)$$

Equation (1) [25] states that the force is being applied perpendicular to the cross sectional area A equates to the tensile stress.

$$\text{Strain} = \frac{\Delta L}{L_0} \quad (2)$$

Equation (2) [25] states that a force is being applied to an object, changing it from its original length to a final length over its original length or $L_2 - L_0 = \Delta L$ divided by $L_0 =$ original length, equates to tensile strain.

$$\dot{Q} = -kA \frac{\Delta T}{L} \quad (3)$$

Equation (3) [27] states that heat is being transferred from a higher temperature object to a lower temperature object through an object medium thickness L with a thermal conductivity of k over perpendicular area of A , equates to heat rate.

Material Design

Composites are highly customizable and can be tailored easily to the necessary applications. The ideal material is one that maximizes the strength to weight ratio and is cost-effective. Preferably a mixture of several materials including a fabric with a 2x2 twill. The 2x2 twill composite structure is the most widely used in the automotive industry due to its high resistance to catastrophic breakage [10], [12], [21]. This material structure which is also called a matrix structure has fibers woven in multiple directions, Figure 4. The matrix material structure ensures that small cracks in any direction of the woven fabric will run into joining fiber without breakage, minimizing the effects of smaller cracks and optimizing the strength to weight ratio.

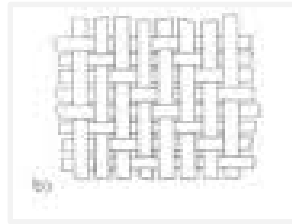


Figure 3: Matrix Structure Material [10]

In order to find the ideal material, two categorically different materials were selected, aluminum and carbon fiber composites, and their properties were analyzed. The 5052-H32 was selected as the baseline for the aluminum series due to its high strength to weight ratio, high weldability, and good resistance to corrosion [4], [14], [15]. Aluminum alloy 5052-H32 is readily available and very cost-effective. The standard prepreg carbon fiber was selected as the baseline for the composite series due to good resistance to corrosion and the ability to tolerate excessive heat [12], [19], [20]. Prepreg carbon fiber has a high strength to weight ratio, low flammability, and the ability to shape and mold easily without cracking.

Based on the factors listed above, it has been decided that the ideal structure for the firewall will be a composite comprised of a carbon fiber base, Kevlar® core with an aluminum foil shield.

Finite Element Analysis

A finite element analysis (FEA) is a three-dimensional computer simulation that allows engineers to analyze a complex structure by breaking it down into small pieces (elements) [1]. The complex structure is then meshed into elements and utilizes numerical methods to solve systems of equations to determine stresses, strains, deformation, safety factor, etc. in the analyzed structure. The FEA results provides a complete picture that predicts if the complex part will successfully satisfy design requirements. In addition, FEA allows engineers to analyze parts in a controlled environment.

Students used FEA to provide a baseline analysis and to determine the material that has the highest strength to weight ratio to build the firewall-seat structure. The firewall must withstand the repeated kickbacks of the drivers in addition to the original purpose of keeping the driver safe from a fire or an explosion. In order to combat the potential for false FEA results and ensure that the firewall and seat base are strong enough, sample lab tests of the combined material will need to be conducted prior to manufacturing.

Data Analysis

Following the design optimization using FEA analysis, students enter the data analysis phase, which should be completed prior to manufacturing. Due to this research being preliminary and completed during the summer, students used data analysis to plan manufacturing techniques.

The FEA run during the summer research season was done in two categories, static force analysis and thermal analysis. During both the static force and thermal analysis series, students used a fine tetrahedral mesh consisting of over 50,000 elements of one centimeter in size, illustrated in Figure 6. During the static force analysis, shown in (Figures 5.a-5.c), a pressure of 240 MPa was used as the applied load along with the attachment boundary conditions from the 2019 chassis. The results of each FEA run in the structural analysis series showed minimal deflection, low stresses, and low strains in the structure, with the exception of the joints. The joints showed some small, but significant areas of high stress, strain and deflection, giving students the insight that when manufacturing the firewall, they will need to structurally reinforce those joints.

During the process of thermal FEA, shown in (Figures 7.a-7.c), students used the same fine tetrahedral mesh consisting of over 50,000 elements with one-centimeter mesh size, running analysis in 6 second intervals from the backside of the component. The applied heat was placed on the heat shield that separates the fuel tank and back of the engine from the driver. The analysis studied temperatures, the total heat flux, and the surface warping. The study used the temperature at the point of combustion of the fuel from the last year's FSAE car, Honda F4i engine. It was concluded that without the air or insulation gap, on the 6 second timeline, the driver could safely exit the vehicle and feel very little temperature change or warping change of the structure. Both series of analyses allowed students to conclude that the design and material selections are optimal, and are able to be safely used with the 2020 chassis.

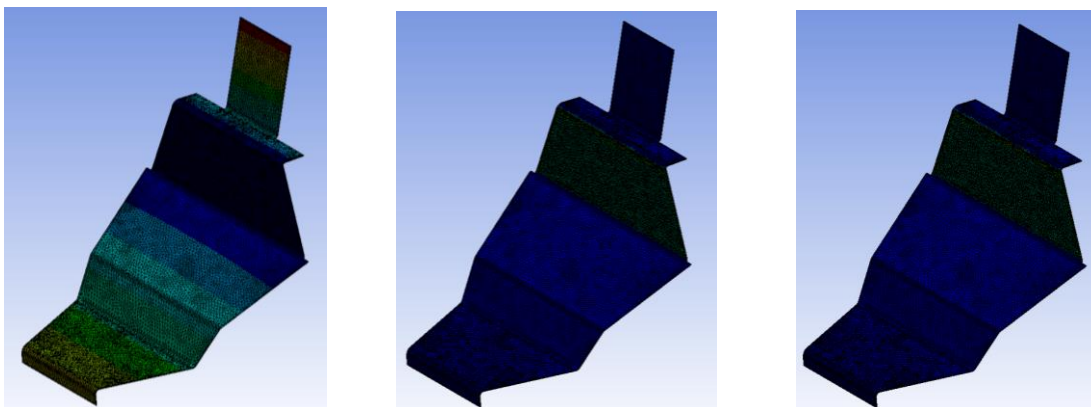


Figure 5: (a) Total Deformation

(b) Shear Strain

(c) Maximum Shear Stress

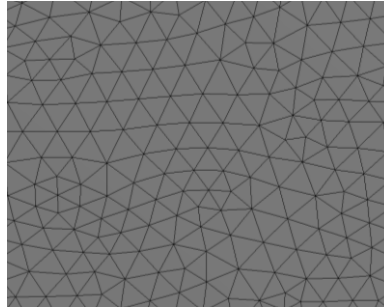


Figure 6: Mesh Structure

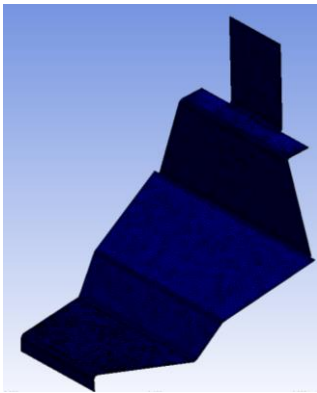
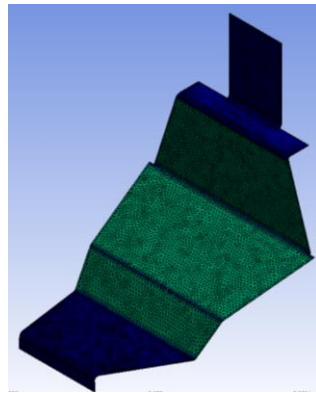
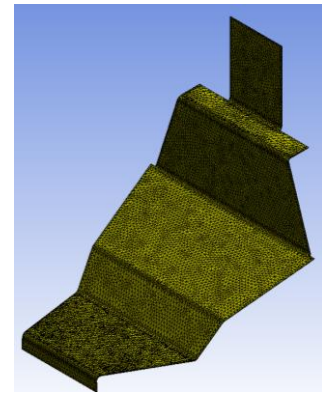


Figure 7: (a) Temperature



(b) Total Heat Flux



(c) Directional Heat Flux

Manufacturing

The female mold for the firewall must be made by starting with a foam base, cut down to size or made with a CNC or machine. After the foam is cut to shape and sanded down, a chemical release agent needs to be applied on top in 3-5 layers on set time intervals. Following the last application of chemical release agent, a surface gel will be applied to create the smooth inside of the mold. The fiberglass will then be applied in three different layers and heated on a time table and to the temperatures listed on the resin by the manufacturer. Once cured, the mold will be sanded down by hand and ready for the carbon fiber layup [6].

The final phase of the manufacturing process will entail doing a carbon fiber layup onto the mold created in the previous step. A template will be created to cut the carbon fiber for the firewall. After the carbon fiber is laid into the molds, finally the vacuum bagging procedure can begin. It is ideal if an oven such as the autoclave is used in order to keep vacuum pressure consistent during the curing process [7]. The temperatures and times necessary for the material depend on which resin is used. After the composite is cured, a fire-retardant core comprised of Kevlar will be added along with a thin aluminum fire shield and foam insulation material to the inside. This will allow for easy grip of the filler foam between the seat and the firewall. Upon completion of the manufacturing process, the firewall and seat assembly can be inserted in the chassis and adjusted to each driver's preference. Both components will then become operational.

Conclusion

In conclusion, the students proved their hypothesis that: in order to have the optimal racing seat and cockpit design configuration that reduces weight, increases driver stability, and improves safety, it is necessary to look at the combined seat and firewall. This should be accomplished by changing the current multi-piece seat and firewall into one cohesive system. The present disjointed weight restrictive system should be changed to an assembly of carbon fiber base, Kevlar core firewall with an aluminum shield, accompanied by cost-effective foam inserts to serve as the seat. This design will increase the driver's comfort and safety while reducing the weight of the vehicle. Students completed this project by learning and applying techniques such as FEA, design optimization, material science analysis and Engineering V as a template. Students involved in this project are a prime example on how first and second year engineering students can be directed to teach themselves through extensive research on how to learn and apply these techniques. Student organizations such as Formula SAE are avenues for students to gain useful exposure to techniques taught in the standard engineering curriculum prior to their third year courses such as, mechanics of materials, heat transfer, FEA, and project management. Projects such as Design and Development of an Integrated Firewall-Seat for Formula SAE Car should be offered to students of all academic levels. The experience will provide greater incentive to pursue an engineering degree as it has for Purdue Northwest students since the team was founded in 2015.

Acknowledgements

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Alana Gorski

Alana is a third-year double major in Mechanical Engineering and Mathematics at Purdue University Northwest, and is entering her second season with Formula SAE. She graduated High School in Washington State in the 2017. She has two years of experience working in AutoDesk Inventor and SolidWorks, as well as a fundamental understanding of Material Sciences. Last year, she completed a research project for the FSAE car, and aided the team in completing the sponsorship packet during the summer. She joined FSAE in order to learn skills crucial to the engineering field prior to learning them in the classroom and prior to the senior design. In May 2019, she was one of the 26 members chosen to travel to the FSAE competition in Michigan. This will be her first project as a primary leader.

Hannah Gross

Hannah is a second-year Mechanical Engineering major at Purdue University Northwest, and is entering her first season with Formula SAE. She graduated from Lake Central High School in Saint John, Indiana in 2018. Prior to college, she took three years of engineering classes and two years of machine shop. Within those three years of engineering classes, she was introduced to software such as AutoDesk Inventor and Revit. This project will allow her to learn the skills to be an effective engineering student prior to her senior design project. Her three years of combined experience using Revit and AutoDesk Inventor gives her an ideal skill set to assist the FSAE team. This is her first independent research project in her educational career.

Dr. Masoud Mojtahed

Dr. Mojtahed is professor of mechanical engineering at Purdue University Northwest where he has been teaching, advising, and performing scholarly activities since 1986. During his tenure at PNW Dr. Mojtahed has served as the Mechanical engineering program coordinator, ASME faculty advisor, SAE faculty advisor, coordinator of Purdue University Technical Assistance Program at PNW, and a member of the university senate and university promotion committees. Dr. Mojtahed also served as faculty visitor and consultant at Argonne National laboratory for five years, and NASA Summer faculty visitor. He is highly active in experimental and analytical research and has over 60 publications in the areas of experimental and applied mechanics. Dr. Mojtahed is an active member of ASME, SAE, ASEE, and served as the chairman of ASME Calumet section for over 10 years.