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Innovative Graduate Engineering Education Implemented with Project-focused Learning: A Case Study—The Clemson University Deep Orange 3 Vehicle Prototype Program

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Abstract

The Deep Orange initiative is an integral component of the graduate program in the Department of Automotive Engineering at Clemson University. The ultimate goal of Deep Orange is to place automotive engineering knowledge into context to tackle complex vehicle development problems through collaboration among students and colleagues whose perspectives are shaped by radically different experiences. During the 2-year MS program, students, faculty, and participating industry partners develop and manufacture a vehicle prototype providing the students with experience in marketing, design, engineering, systems integration, prototyping, and validation. For the third edition of Deep Orange, the goal was to develop a blank sheet, fully functional, hybrid mainstream sports car concept targeted towards Generation Y with Mazda North American Operations as the primary sponsor and the Art Center College of Design as the styling partner.

The objective of this paper is to present a case study for the development of the unique Deep Orange 3 body-in-white (BIW) prototype vehicle structure. The size and proportions of the BIW concept were developed based on the requirements derived from a marketing study based on 70,000 surveys completed by owners of new cars and light trucks in the United States. Based on the findings of the marketing study, a sports car concept was derived for a 6-seat interior configuration and a body architecture packaging a dual-mode hybrid all-wheel drive powertrain. In addition to developing an efficient body structural lay-out, an additional objective of the program was to develop and showcase a BIW concept that would eliminate metal stamping and the associated high investment costs associated with this technology (such as stamping tools and dies). It was chosen to investigate and apply Industrial Origami's patented technology that incorporates light-gauge metal folded into complex, high load-bearing structure, formed with simple, low-cost fixtures at the location of BIW assembly.

Developing the geometry, topology, and functionality of the BIW based on these design and manufacturing requirements required intensive collaboration among design students and chassis, vibration, powertrain, and packaging engineering students, while at the same time integrating functional properties, weight, cost, and design space. The BIW engineering discussed in this paper focused on defining relevant load cases (such as static/dynamic stiffness properties), developing a structural configuration to efficiently transfer BIW loads, creating occupant accommodation space, packaging of powertrain and chassis components, and conducting computational analyses to assess BIW stiffness and strength. Once the structural performance targets were met, the final sheet metal folded design was realized using aluminum in combination with adhesives and rivets. In addition to describing the conceptual structural analysis, the paper elaborates on the team collaboration required to achieve the final realization of the BIW structure.

Introduction

Engineering education in the US has relied on traditional methodologies that have struggled to provide early-career engineers with skills and experiences needed to succeed in today's fast-changing technical fields. Current approaches to engineering education are generally the same as those employed during the last century and date back to the early 1940's[1]. A recent study by the American Society of Mechanical Engineers (ASME) identified current features of US engineering education that are ineffective with a focus on mechanical engineering[2]. The most significant shortcomings were internship experiences, a general system-level design perspective, a knowledge of engineering standards and codes, problem solving skills, written and oral communication skills, and project management skills. To close the gap between current engineering education practices and those identified changes, ASME recommended the following actions for curricular change: (1) Create curricula that inspire creativity and innovation (professional skills such as entrepreneurship, teamwork, problem solving, and project management), (2) Initiate more project-based engineering experiences that are based on design portfolio or design spine approaches[3], (3) Incorporate "Grand Challenges" into the design spine (such as lightweight design, sustainable development, and energy efficiency), and (4) Increase faculty experience in professional practice.

Based on these recommended actions, current engineering education requires significant modification based on the implementation of dynamic curricula that can rapidly respond to industry needs and at the same time can focus on the requirements of traditional engineering. For example, the design, manufacture, and implementation of efficient road transportation systems based on autonomous vehicles requires an integrated application of design concepts from disciplines ranging from automotive engineering and sensing/information technology to business management and behavioral science. Many challenges and opportunities for improved autonomous vehicle design have recently arisen in the road transportation industry as a result of rapidly changing technology, intense competition among current vehicle manufacturers and information technology companies, and changing transportation regulations and public policy. The rate of market change has dramatically increased the need for an engineering work force that can manage and lead product development processes that require increased innovation over reduced time-to-market product development cycles.

An engineering education approach to develop these needed innovation skills requires systems focused project-based learning. Studies[4] have shown that this teaching structure can meet the needs for active learning to develop robust professional skills which greatly depend on design integration and creativity, as in the case of autonomous vehicle engineering. The Automotive Engineering Department at the Clemson University International Center for Automotive Research (CUICAR) has created an educational framework that incorporates this project-focused approach within a component of their graduate curriculum known as Deep Orange (DO). The DO initiative[5] was developed to provide graduate students with hands-on experience of vehicle development knowledge in various engineering disciplines and related fields (such as marketing and human factors psychology).

Deep Orange Program Summary

The Deep Orange initiative was launched in 2009 as a partnership with the Transportation Design Department of the Art Center College of Design in Pasadena, California. The Automotive Engineering curriculum at Clemson merges the depth (through specialized tracks) and breadth (through the interdisciplinary Deep Orange initiative) into an integrated scholastic experience. DO is a framework that immerses students into the world of a future Original Equipment Manufacturer (OEM) and/or supplier emulating an accelerated product development process for a new vehicle. Working collaboratively, students, multi-disciplinary faculty, and participating industry partners focus on designing and building a new vehicle concept with each new class of students. Industry participation and mentoring plays an essential role in the process.

Each DO project incorporates integrating innovations for breakthrough products and new processes, which provide the students with hands-on experience in multi-disciplinary fields, such as market analysis, value proposition creation, vehicle design, computer-aided engineering, systems integration, prototyping, and design validation from their entry into the automotive engineering program until graduation. The strategic focus of DO is to develop new automotive mobility solutions that address a grand challenge (such as sustainability, safety, health, and wellbeing). Currently, DO is in its ninth series with the two-year program divided into six main design stages (Figure 1).

- Strategy and market assessment, identification of opportunities, and creation of a value proposition
- Ideation, solution formulation, and concept selection
- Concept development (detailed engineering and design)
- System integration (design space, function, production)
- Prototype build and assembly
- Product validation and target confirmation

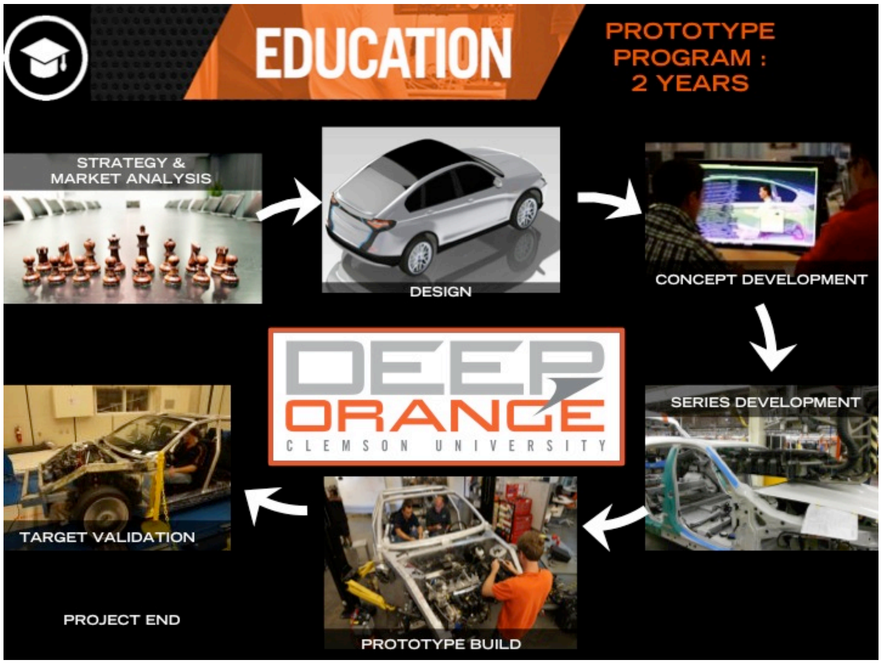


Figure 1. Six Main Design Stages for the Deep Orange Program

The development cycle for the vehicle design initiates the project with the value proposition and definition of customer needs. The students are required to justify all of the generated program solutions and concepts within the context of the derived customer needs. This design methodology allows for the confirmation of design specifications to the initial targets. The following presents a case study for the Deep Orange 3 body-in-white (BIW) prototype vehicle structural development to illustrate the project-focused educational features of DO.

Case Study: Deep Orange 3

The goal of the DO3 Project was to develop a blank sheet, fully functional hybrid mainstream sports car concept targeted toward Generation Y. Mazda North American Operations was the primary sponsor and the Art Center College of Design in Pasadena, CA was the styling partner. A key technical project objective was to develop a structural body concept that will eliminate body stamping and the associated high capital investment for vehicle production. The program chose to explore Industrial Origami's patented technology that uses lighter-grade material folded into complex, high-load bearing structure, formed with simple low-cost fixtures at the point of assembly[6]. This case study illustrates the value proposition, vehicle architecture definition/development., and body-in-white (BIW) assembly for the project.

•**Value Proposition Formulation.** The marketing objective of this DO project was to develop a concept vehicle for Generation Y with Mazda as the core brand and a Manufacturer's Suggested Retail Price (MSRP) between $20K and $30K. The vehicle concept to be developed was given the name "Next Big Thing" (NBT) and was the first DO project built from scratch. In order to derive a value proposition, it became necessary to understand the brand essence and conduct marketing studies on the Generation Y demographic.

The target customers, as defined by Mazda, were “Those individuals who stay young, have a good capacity to express themselves, are always passionate, and are self-confident in their choices”. This statement clearly shows that the Mazda brand does not target certain demographics. It was a deliberate choice of the DO program to deviate from the generationally independent Mazda target customers in order to explore more specific unique aspects of the Generation Y target segment. The brand DNA, as defined by Mazda, is characterized as “Stylish”, “Insightful”, and ‘Spirited”, with product attributes characterized by “Distinctive Design”, Intuitive Function”, and “Responsive Drive”. These attributes were followed throughout the entire concept definition phase to assure that the NBT concept vehicle could be perceived as a true Mazda vehicle, not only by its exterior/interior design, but also by its functionality.

The unique BIW developed for this project was based on the specific design requirements derived from a marketing analysis based on the target customer characteristics discussed above. The marketing analysis was based on 70,000 surveys completed by owners of new cars and light-duty trucks in the US. The Analyses revealed that Generation Y, as an environmentally conscious and social-savvy generation, prefers to travel together in one single vehicle. The survey data clearly indicated that a large portion of that generation would prefer a sporty vehicle with 5 or more seating positions. In addition, the marketing data revealed that Generation Y is willing to invest in sustainable powertrain technologies with a significant emphasis on all-wheel-drive (AWD) capability, particularly in the northern regions of the US. The overall value proposition for the NBT project concept vehicle was derived by combining all of these marketing aspects and is summarized in the diagram shown in Figure 2.

“Green still means go!”

- Hybrid powertrain (IC & Electric)
- All wheel drive
- Manual transmission

“Mazdafication”

- Digital dashboard
- Interchangeable body panels and interior components
- Expressive lighting (exterior and interior)
- Assignable sound effects to powertrain and vehicle functions

“All Win Drive”

- Seating for 6
- Easy Ingress/Egress of occupants and cargo
- Stationary activity
- Device connectivity (communication and power)

Figure 2. NBT Value Proposition Summary

•**Vehicle Architecture Definition & Development.** The final architecture for the vehicle was defined and developed by applying technology and packaging solutions which comprehended all relevant engineering perspectives, including function, geometry, and production. The solutions addressed the program marketing imperatives related to vehicle performance, customer usability, and manufacturability.

The NBT vehicle architecture, as shown in Figure 3, places a traditional internal combustion engine, including a manual transaxle, in the front of the vehicle to drive the front wheels. The rear wheels are driven by electric motors packaged at each wheel. This powertrain configuration enables the vehicle to achieve required torque delivery to each wheel as well as decreased fuel consumption through regenerative braking and optimized engine operation. Batteries for the rear wheel drive motors are placed underneath the rear seat for passive safety as well as packaging reasons.

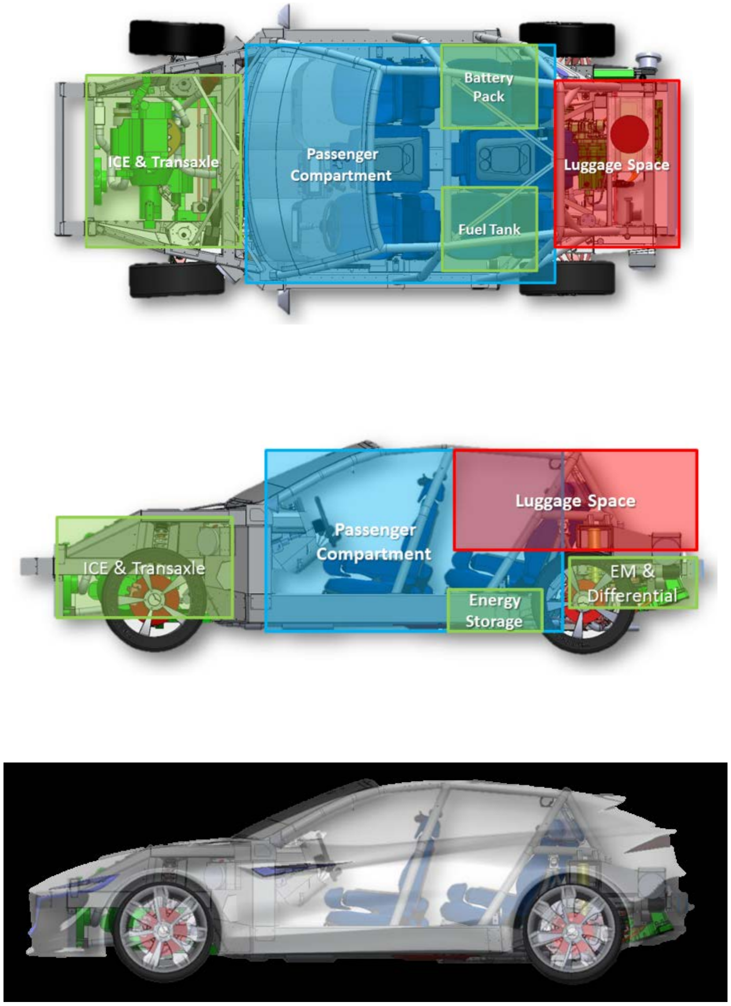


Figure 3. NBT Vehicle Architecture

The selected powertrain configuration eliminated the need for a center vehicle tunnel which typically houses the transmission and drivetrain. The NBT concept only required a small tunnel size to package the exhaust system. This enables increased packaging space for the interior cabin to accommodate the 6 target occupants. To provide adequate occupant packaging and storage space without compromising ingress or egress for passengers or objects, a three-seat, two-row interior configuration was selected. The vehicle side closure panels include approximately equal length suicide doors and a rear tailgate hatch. This configuration supports marketing imperatives of increased usage of the vehicle while stationary (i.e., tailgating or similar). Vehicle seats with fold-flat capability were utilized to meet program luggage capacity targets.

In order to provide a sporty driving experience, a double-wishbone suspension system was selected for the front and a multilink configuration was selected for the rear. The vehicle was also packaged with a low seating position and a dash-mounted manual gear shift lever to further support the required sporty appearance.

The specific overall vehicle dimensional properties based on this architectural configuration, shown in Table 1, were developed from the inside-out using targets derived from benchmarking existing vehicles in the sporty car and hybrid/electric car market segments.

Table 1. Basic Vehicle Properties

Length	4.450 mm
Width	1,905 mm
Height	1,350 mm
Ground Clearance	110 mm
Wheelbase	2,730 mm
Acceleration, 0-60 MPH	7.5 sec
EPA Combined Fuel Economy, MPG	45 MPG
Curb Weight	1,400 kg
Target MSRP for 2015 Model Year	$27,995

Based on these benchmarking targets and the program marketing analysis, a “4+2” seating layout was developed as shown in Figure 4. The four outer seats accommodate 95th percentile American males and the two middle seats accommodate 50th percentile American males. RAMSIS® ergonomics design and analysis simulation tools were applied to develop this interior concept.

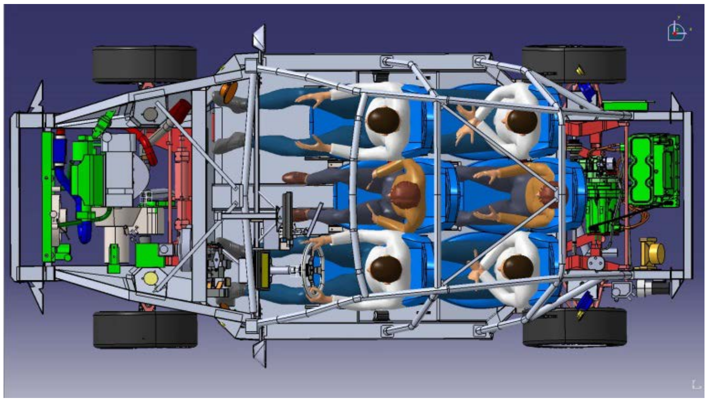


Figure 4. Vehicle Occupant Layout

During the vehicle architecture development process, a BIW structural topology was built around the occupant packaging design, giving a high priority to realizing the interior space requirements while meeting structural performance targets. The functional BIW development targets for mass, torsional stiffness, and bending stiffness were derived based on competitive benchmarking data of existing unibody vehicles as well as market regulations for safety.

Figure 5 illustrates a large sample of mass data for modern unibody vehicles (steel, aluminum, and mixed-material designs manufactured between 2000 and 2012). The trend line indicates a linear relationship between the BIW weight and the total vehicle curb weight. Based on this linear relationship and the NBT target curb weight (1,400 kg), the program target for an aluminum BIW without closures (hood, doors, deck lid) was 210 kg. The target with closures was estimated to be 266 kg.

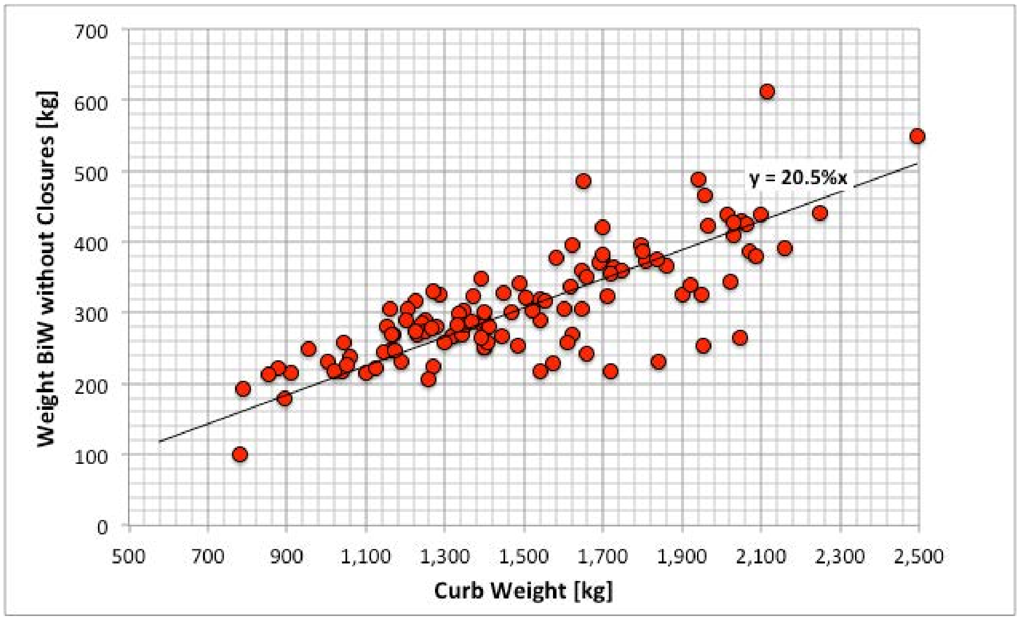


Figure 5. BIW Weight as a Function of Vehicle Curb Weight

Similar linear-trend benchmarking data was applied to determine targets for BIW torsional and bending stiffness. Figure 6 shows that a linear trend exists between BIW torsional stiffness and vehicle curb weight for 3-box type vehicle designs. Since the NBT concept vehicle is a 2-box design, the benchmarking data provides a static torsional stiffness target of 18,480 N-m/deg. Using a similar linear-trend relationship between the BIW static bending stiffness and vehicle curb weight for unibody benchmarked competitive vehicle, the program static bending stiffness target was set at 9.800 N/m.

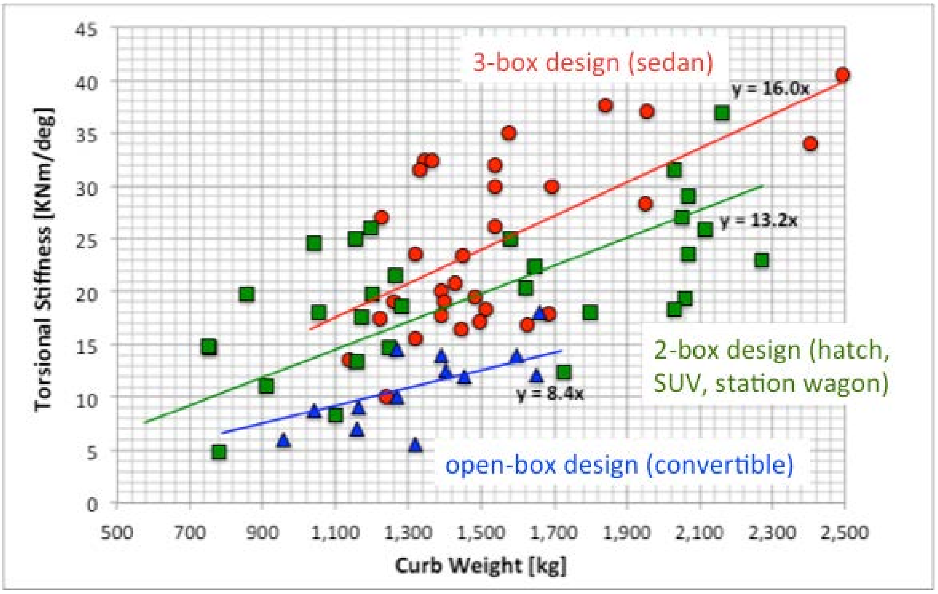


Figure 6. BIW Torsional Stiffness as a Function of Curb Weight

The initial NBT BIW topology was developed based on structural studies of production vehicles such as the Mazda 2 and the BMW 1 Series. An example figure from this study, Figure 7, shows front crash load paths for a BIW. Similar figures were applied for rear crash, side crash, cornering loads, and braking loads. Load flow structural studies for the three crashworthiness conditions determined the overall shape of the structure while balancing packaging requirements for exterior design, interior, and chassis components. The cornering and brake load flow studies were used to strengthen the structure locally at chassis mounting locations. The completed initial BIW structure is illustrated in Figure 8, as rendered using SolidWorks®.

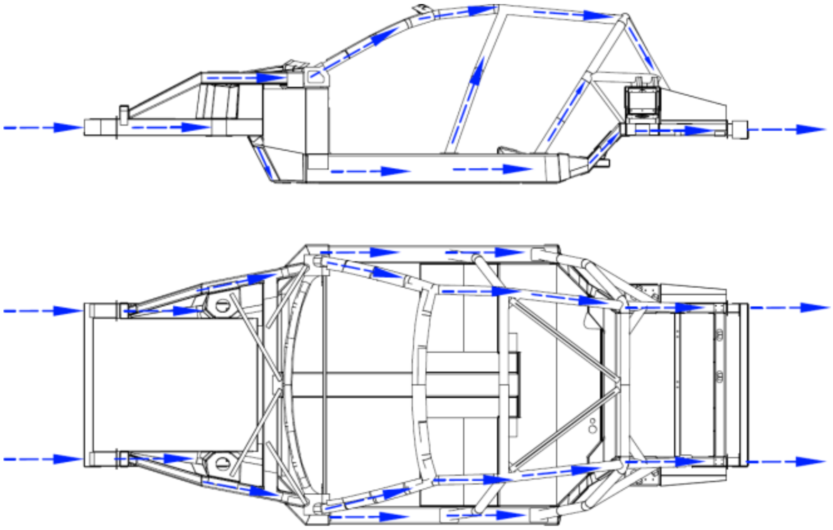


Figure 7. Front Crash Load Paths

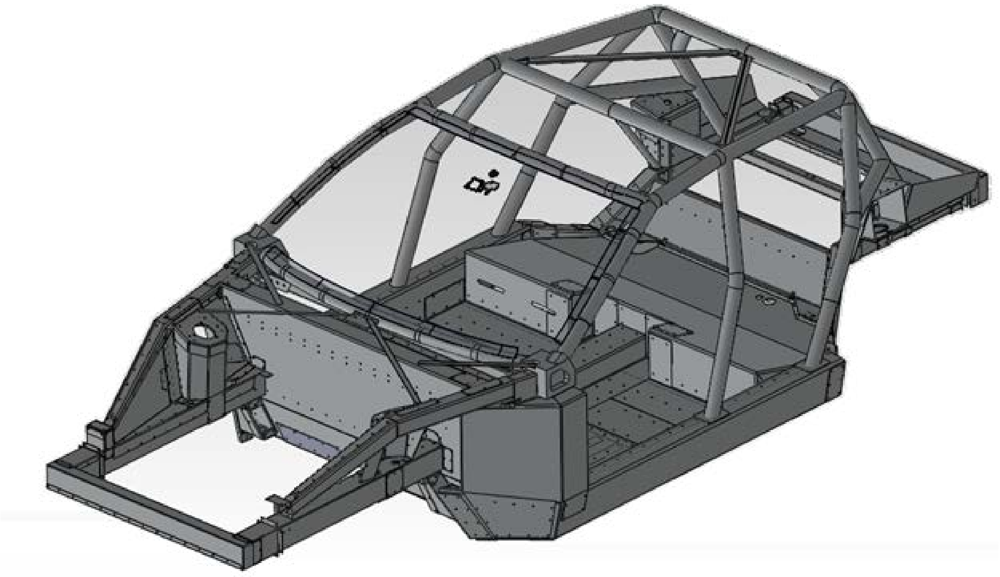
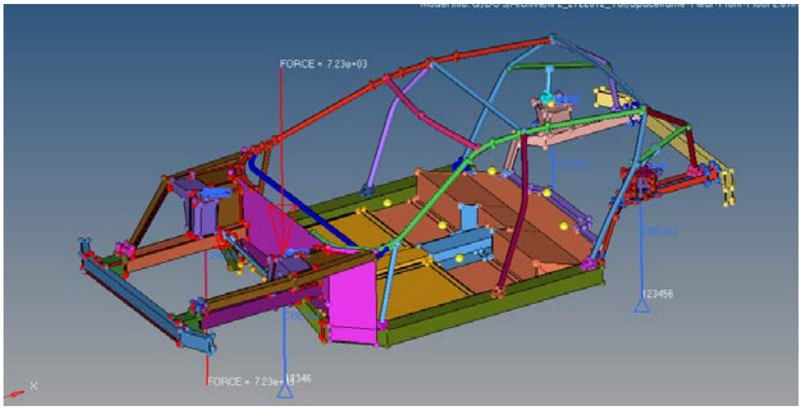
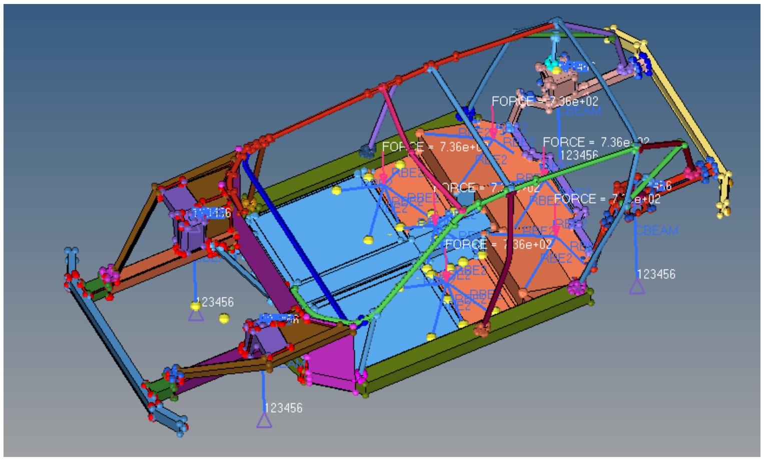


Figure 8. Initial BIW Structural Design

After completing the initial BIW design using SolidWorks®, the three-dimensional data was imported into the HyperWorks® computer-aided-engineering suite for structural finite element analysis. The primary goal of the structural analysis was to achieve the static torsional and bending stiffness targets through topology changes to the cross-sectional design and thickness of structural members. Due to time constraints placed on the program BIW structural development, only two load cases, one for torsion and another for bending, were considered for static finite element simulation. For the torsional simulations, static axle point loads were applied at the center of each of each of the front suspension strut towers, as shown in Figure 9a. The rear strut towers were modeled to behave as ball joints. For the bending simulations, the major vertical loads acting on the BIW represent the gravitational loads of six occupants with 75 kg placed at each of the seating locations. The four strut towers were fixed and modeled as ball joints, as illustrated in Figure 9b.



(a) Loads and Boundary Conditions for Torsional Stiffness Simulation



(b) Loads and Boundary Conditions for Bending Stiffness Simulation

Figure 9. Loads and Boundary Conditions for Determining Static Torsional and Bending Stiffness

The torsion and bending simulations were conducted to identify the major shortcomings of the initial BIW design to achieve the desired torsion and bending stiffness. Structural modifications involved thickness and cross-sectional width/height changes to individual structural members based on stress levels and load transferring capability. Structural members were added to the BIW, such as a torsion plate behind the rear seat, to increase load path effectiveness. BIW joint efficiency was also increased through the addition of local reinforcement members. All structural changes were implemented simultaneously in the development CAD model to identify potential areas of interference resulting from component packaging. Torsional stiffness improvements are summarized in Figure 10. After seven major iterations, the torsional and bending stiffness targets were adequately achieved (18,480 N-m/kg and 8,000 N/m, respectively).

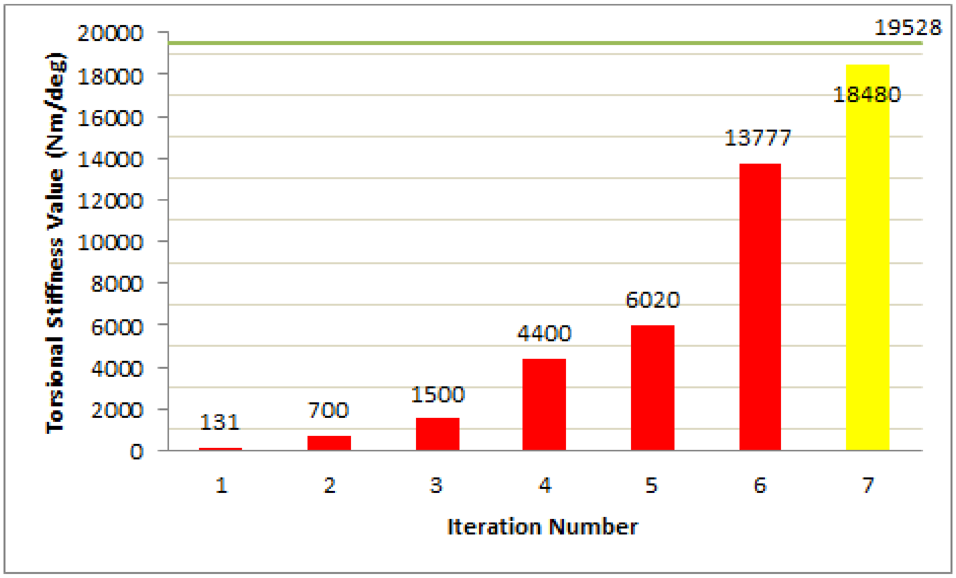


Figure 10. Design Iterations for Torsional Stiffness

Additional simulations were carried out to ensure that the BIW structure was stiff and strong enough to support concentrated loads at all suspension and powertrain mounting locations under driving conditions. Several static load cases were developed to simulate maximum acceleration, maximum braking, and maximum cornering loads for a fully-loaded vehicle. Statically-equivalent loads were determined by modeling the NBT in the multi-body simulation package, Simpack®. The resulting loads applied to HyperWorks finite element models helped to assess local stiffness and strength at various strut tower, sub-frame, and powertrain mount locations. Local stresses were required to be below the yield strength of the aluminum structural material (Alloy T6061-T6). Additionally, local stiffness of the BIW at each load point were required to be a factor of 10 greater than the local mount bushings to assure adequate acoustic isolation of the mounts. Figure 11 shows an example of a local reinforcement design change where sleeves were added inside the front lower crush rails at the front sub-frame joint location.

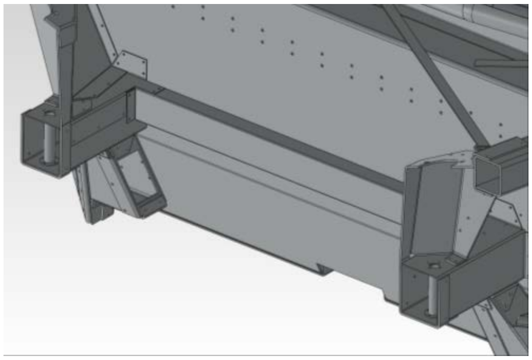


Figure 11. Sleeve Reinforcement Inside of the Front Crush Rails

•**BIW Manufacturing & Assembly.** This section explains the implementation process of a folded sheet metal structure as applied to automobile manufacturing and emphasizes important intricacies in working with this medium for improving design and manufacturing, particularly in a prototyping environment. Summaries of the cardboard mockup construction, sheet metal fabrication, and space frame build are provided in the following.

After reaching a mature BIW design in terms of achieving functional, geometric, and assembly design targets, a 1:1 scale mockup built out of cardboard was constructed in order test the manufacturing of the structure (Figure 12). Cardboard sub-structural components were fabricated by folding corrugated cardboard sheets in a manner similar to that which would be used later for the final aluminum build. Bonding of the folded cardboard components was achieved using standard hot melt adhesive, the type used in hobby craft applications. Due to the materials and tools used for construction, the mock build was not applied for accurate geometry verification or functional evaluation. Despite these limitations, a relative dimensional check was performed. Additionally, insight was gained in the areas of component foldability, as well as assembly sequence and tool accessibility.

Figure 12. NBT Cardboard Mockup

The BIW sheet metal fabrication process was initialized by component featuring which is dependent on material thickness. Feature geometry was provided by Industrial Origami, along with an explanation and rationale for applying features for the various types of folds. After the featuring had been completed, drawings were sent out to selected vendors for manufacture. The body structural components received from the vendors arrived as flat-cut sheets, as shown in Figure 13. After thorough component sheet inspection, the folding process was initiated. The NBT BIW required 40 individual pieces to be folded. The structure was designed so that 4 main sub-assemblies could be produced and then combined. This enabled a parallel build that required more resources, but decreased the total build time. For the folding of each component, consideration must be given to the total number of folds that need to be made and the order in which they need to be folded, particularly with regard to flange overlap, as well as the tooling that is used. For example, overlapping flanges that box out should not be folded completely as adhesive will not be able to be applied correctly over the surface.

Figure 13. BIW Structural Components before Folding

The specific folding technique was derived from the art of Japanese paper folding, where the features help to decrease the required fold force and predefine a fold line by creating a “perforated edge” type pattern across the material plane and through the material thickness. This allowed for a reduction in the fold force and thicker aluminum sheet to be folded by manual human effort, using only basic tools such as torque bars. A portion of the folding process required a given component to be secured flush against a static surface on one side of the fold line. A basic free-body-diagram illustrating the required component constraint forces for the fold technique is shown in Figure 14.

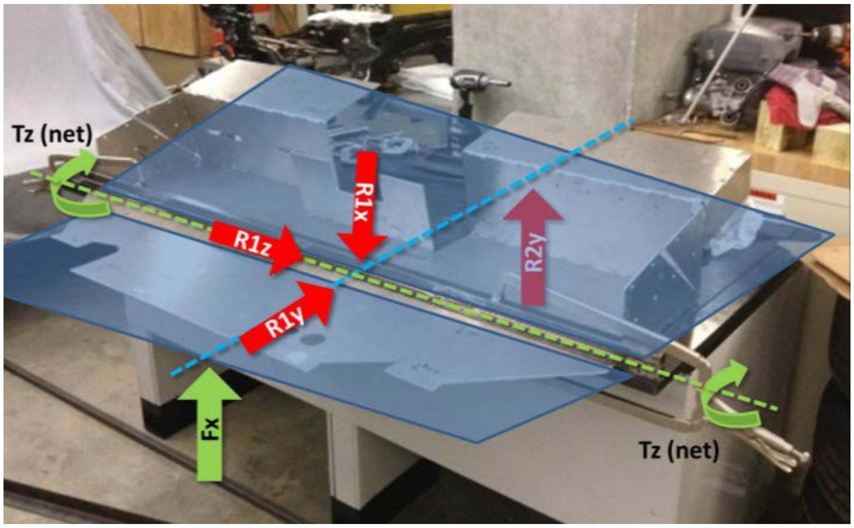


Figure 14. Free-Body-Diagram for Basic Fold Technique

The final step for processing a folded sheet metal BIW component is to secure the adjacent folded edge with adhesive. Before applying the adhesive, a test fitment of all the folded structural pieces without adhesive application needed to be completed. For the NBT structure, a mixture of temporary fasteners, such as clamps, standard bolts and nuts, and rivets were applied. The final test assembly before adhesive application is illustrated in Figure 15.

Figure 15. Final Test Assembly of Folded BIW Components

The adhesive chosen for the final assembly was Loctite® H3151. This adhesive provides superior bond strength for shear loading, as well as the capability to bond to both aluminum and steel surfaces. Additionally, the adhesive remains relatively stable over the range of temperatures that a vehicle would be exposed to throughout its lifetime. The cure time of this adhesive was particularly important to its selection as large faces need to be coated evenly and mating parts need to be aligned. These actions took time and couldn’t be rushed. Additionally, clamping and riveting needed to be completed just after contact of the adhesive to the adjoining surfaces. The selected adhesive has a cure time of 45-60 minutes with a fixture time of 60-120 minutes. These times were adequate to complete the fastening processing of individual BIW components and the final assembly of the space frame structure.

The final step of the BIW construction was accomplished by bonding the folded components to a space frame structure. Key elements for space frame fabrication were A-Pillar, B-Pillar, and C-Pillar structural nodal joints needed for joining the space frame members using adhesive bonding. The structural pillar blocks comprising these nodes were machined in-house from aluminum blocks with a 5-axis CNC machine. Design data for structural node cutting was imported from SolidWorks®. Before cutting a stock block of aluminum with the CNC machine, a wooden block (Figure 16) of the same dimensions was used to check for errors in the program code for the machine operation. Passenger and driver-side structural nodal joints were designed to be mirror images of each other. Fabricating the structural joints in-house saved considerable time and money when compared to outside supplier fabrication.

Figure 16. Wooden Block for A-Pillar BIW Space Frame Nodal Joint

The strength of the space frame could not have been achieved if the tubes had folds on the interior side of a tube bend. Initial tube processing was completed using a mandrel bender. However, it was found that the tubes developed cracks when so bent. Experiments were completed to investigate techniques for non-mandrel bending. It was found that applying a CNC bending machine without the use of a mandrel was adequate for forming bent tubes without surface folding or cracking. The final NBT concept vehicle space frame is shown in Figure 17 with 6 seated occupants.

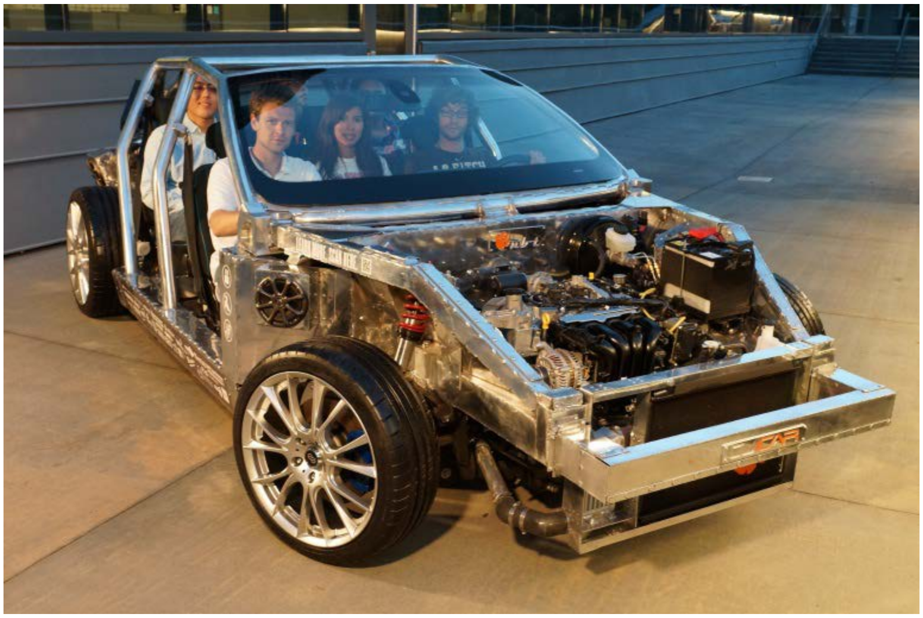


Figure 17. Final NBT Concept Vehicle with 6 Seated Occupants

Summary & Conclusion

This paper presented development of the topology, geometry, and functionality for a unique body-in-white concept design that offers accommodation for 6 passengers and includes a dual-mode hybrid all-wheel-drive powertrain. An additional objective of the Deep Orange Project was to develop and showcase a BIW concept that will eliminate metal stamping and high capital investment associated with BIW manufacturing (Such as dies and stamping tools). Deep Orange 3 selected to explore the Industrial Origami patented technology that allows using lighter gauge material folded into innovative, high-load bearing structure, formed with simple low-cost fixtures. The structural development of the BIW required intensive collaboration among design students and chassis, vibration, powertrain, and occupant packaging engineering students while carefully balancing functional properties, design space, cost, and weight. Once the design targets and properties were met, the complete sheet folded metal technology design was completed using aluminum and structural adhesives.

The goal of Deep Orange, to place academic knowledge into context and tackle complex vehicle design problems through collaboration, was successfully achieved through this unique Deep Orange 3 Program industry-academic partnership.

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