

Mechanical Coupling due to Composite Structural Damage and Repair

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ABSTRACT

The research described examines the relationship between damage/repair scenarios and the resulting effect on the coupled response of the structure. The monocoque is simplified as a box beam and damage is simulated by introducing a hole in one side of the tube. Repair is simulated by adding plies to an undamaged area of the beam side. Composite beam samples were manufactured and tested using a 3-axis coordinate measurement machine (CMM), to experimentally verify the computer numerical predictions of the deformed shape. The beams were loaded with a combined torsion-bending load using an eccentric tip load and rigidly fixing the opposite end. Structural coupling was observed by computing the distortion center of the beam profile at cross-sections along its length and comparing the results to the undamaged/unrepaired beam. The experimental results correlate well with the finite element simulations and generally follow the predictions of the analytical model. It is found that both torsion-bending coupling and asymmetric torsional stiffness occur for both the damaged case and after structural repair.

INTRODUCTION

The singular choice of materials for manufacturing the monocoque of modern open wheel racecars are fiber-reinforced composites. In motorsports, structural coupling of the monocoque is, in general undesirable as it would lead to unpredictable response of the vehicle, such as compliance in roll and heave that cannot be accounted for in the suspension design. For this reason, the laminate, and structure, must be symmetric from right to left about the centerline of the car. This will be the case unless the monocoque is damaged. If the extent of the damage is not severe enough to warrant replacement of the entire monocoque, repairs are made to the monocoque to regain the structural integrity. Unfortunately, an artifact of the repair process may be an imbalance in the amount of material from side-to-side in the monocoque. It is hypothesized that this asymmetry

inadvertently produces a torsion-bending couple in the monocoque.

The motivation for this research stems from conversations in early 2006 with engineers and drivers in the Champ Car® World Series in which it was indicated that the driver would not drive a certain chassis after it had been crashed because, after repair, the response of the car was inconsistent in left and right hand turns. The extent of the sustained damage and subsequent repair of such "undriveable" chassis was not available outside of the chassis manufacturer, but it was assumed that the vehicle would not be repaired if the damage was significant enough to deem it a total loss.

In 2006, the chassis of choice in Champ Car® was the Lola B02/00, a composite monocoque incorporating composite internal bulkheads and aluminum honeycomb core. Although the actual layup construction of the monocoque is not published, the 2001 CART rule book states that the monocoque laminate must be quasi-isotropic [1]. It is assumed that the layup is also symmetric and balanced about the xz-plane of the vehicle (see Figure 1 for vehicle coordinate system).

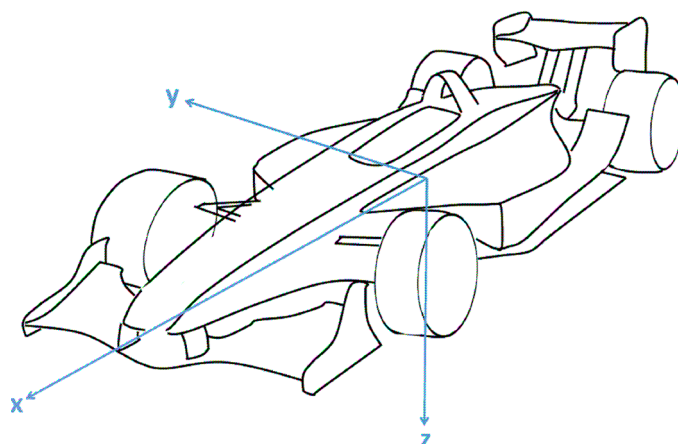


Figure 1: SAE vehicle coordinate system

The monocoque serves the dual purpose as the primary load bearing structure of the vehicle as well as providing a high degree of driver safety. The carbon fiber laminate that skins both sides of the core provides the majority of the bending and torsional stiffness. The core resists shear loads and greatly increases the local buckling resistance of the structure.

In the event that the monocoque is damaged, for example, by an impact to one of the front corners that drives the anti-penetration bar into the side of the structure, it is likely that it will need to undergo some type of repair. These repairs may range from minor, for example repairing damaged suspension hardpoints, to major, such as removal and replacement of the affected area. In the either case, extra material (e.g. prepreg, core, etc.) is usually added to regain the structural integrity that was compromised. At a minimum, the new laminate used in the repair must be larger than the damaged area in order to tie in continuous fibers across the region (Figure 2).

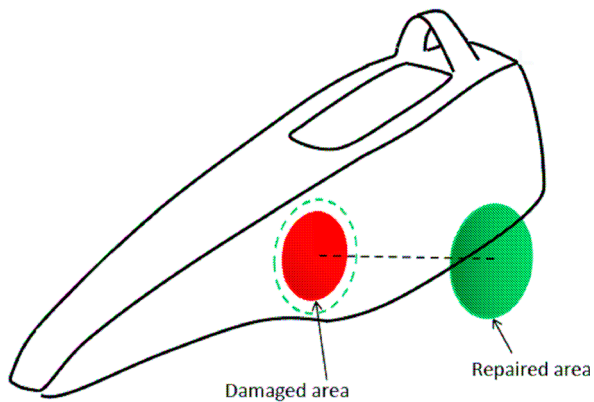


Figure 2: Comparison of large repair area to smaller damaged area

Accordingly, it is possible to double the number of plies in the region of overlap. The effect of this material “imbalance” about the xz-plane is the driving force behind this research.

It is important to note that while the cockpit opening in itself might be considered a “damaged” region of the monocoque, resulting in a decrease in the torsional stiffness of the structure, it is symmetric about the vehicle roll axis. However, damage, or repair, to a side of the monocoque is not symmetric about the roll axis, and it is predicted that the repair process leads to lateral torsion-bending coupling that is the cause of the unpredictable performance of the racecar. While it is likely that the cockpit opening also leads to a bending-torsion couple, it is expected that this couple results in bending in the vertical direction that is not a function of the rolling (torsion) direction.

Previous research has investigated the effects of torsional stiffness on racecar monocoque performance and measured the torsional stiffness in a variety of

ways [2][3][4]. Research has also been undertaken to attempt to assess position, and level, of damage of a racecar monocoque through torsional stiffness evaluation over the length of the chassis [5].

The current research goal is to show that the structural coupling can be found by measuring the lateral displacement of the center of cross-sections along the length of the chassis. It is hypothesized that the line representation of these centers, referred to as the distortion center will always “bend” laterally toward the softer (less stiff) side of the structure for both right- and left-hand torsion. In both cases, the structure exhibits unfavorable mechanical coupling where combined torsion-bending loading also results in lateral (transverse) bending.

BACKGROUND ON TORSION

The problem of torsion is one of the most famous problems in engineering. The knowledge base is extensive and broad, spanning almost 150 years since St. Venant's work on the torsion of prismatic sections. Significant work on torsion of thin-walled beams was done by Argyris and Dunne [6], von Kármán and Christensen [7], Bescoter [8], Vlasov [9], Waldron [10], Reissner [11], and Gjølvik [12] on isotropic beams.

The bulk of the research regarding torsion of thin-wall composite beams has taken place in the last 20 years. The most cited work in the development of thin-walled composite beam theories is that of Vlasov, the basis of which is the replacement of the plate stress resultants, displacements, and load distributions with equivalent beam forces, couples, displacements and load distributions that are independent of the contour coordinate. Vlasov theory applies to both free and restrained torsion by accounting for section warping. When applied to composite beams, however, transverse shear strains must be accounted for to correctly estimate the beam stiffness. Mansfield and Sobey [13], Chang and Libove [14], and Loughlan and Ata [15] have proposed composite beam theories without taking transverse shear or section warping into account. These models were improved by Reddy [16] and Noor and Burton [17]. Stemple and Lee [18] presented a finite element formulation capable of modeling combined loading and included warping effects. Bauld and Tzeng [19] proposed linear and non-linear Vlasov theory for open-section beams disregarding midplane shear strains. Bauchau [20] developed a warping model using variational principals for closed-section beams with anisotropic walls. Chandra and Chopra [21] provided a theoretical study of thin-walled general laminate composite beams based on Vlasov theory and accounting for transverse shear deformation. Pluzsik and Kollár [22], Song and Librescu [23] and Salim and Davalos [24] extended this theory for both open- and closed-section beams by accounting for the tangential stress.

The focus of the present research requires knowledge of restrained torsion of thin-walled composite open- and closed-section box beams. The unique aspect of this research is that no numerical treatment exists, except for finite element methods, concerning the problem of composite closed-section box beams which also have an open cross-section (Figure 3) or asymmetric distribution of material along the length and width of the beam (e.g. a plydrop) (Figure 4).

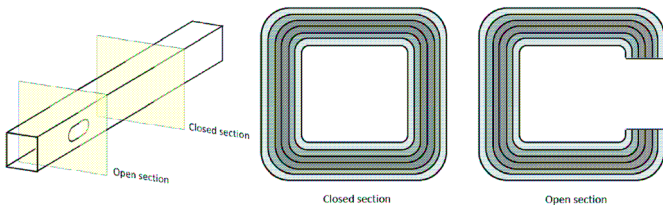


Figure 3: Open cross-section segment of damaged box beam

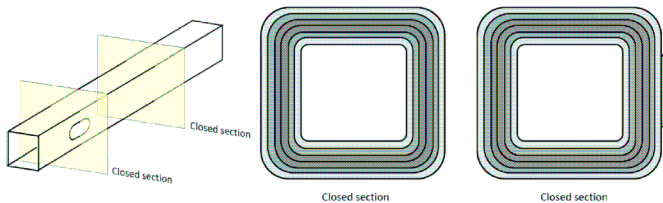


Figure 4: Plydrop forming closed cross-section segment of repaired box beam

It is noteworthy that Benscoter [8] formulated an approximate but sufficient solution to the problem of thin-walled beam torsion, which applies for beams with stiffened or unstiffened sections. Although the repaired box beam case from this research at first appeared to fit this classification, it soon became clear that this prior work was devoted to multi-cell box beams where stiffeners maintain the cross-section contour, running the full width of the beam. The “class” of damaged and repaired composite box beams seen in this research cannot be simplified as a series of discrete 2-D cross-sections because the governing equations are not the same along the beam length. In reality, these beams exhibit complex structural effects that are difficult to analyze using standard elasticity approaches.

Although the composite box beams unique to this research do not appear to fit any classification given in the literature, some numerical and empirical work has been done with isotropic circular tubes with holes and similar loading conditions. Montague [25] investigated circular, thin-walled steel tubes with elongated, non-axisymmetric openings subjected to compression, torsion, and bending. He established that the behavior of the tube has characteristics such as stress concentrations at the hole opening, large displacements of the free edge at low load, and stress redistribution at the cut-out cross-section due to local instability of the free edge, which he found difficult to analyze. Almroth and Brogan [26] presented a numerical solution for the

buckling of a cylinder with symmetrically placed rectangular holes, including holes with discrete stiffeners in the vicinity of the cut-out that seemed to match closely with experimental results. Eiblmeier and Loughlan [27] conducted lengthy experiments on the buckling of flat composite plates with centrally located circular holes with and without ring stiffeners. Their experiments were validated with FEA. However, no theoretical, analytical, or experimental work was found that treated a case similar to the repaired box beam case shown in Figure 4.

RESEARCH APPROACH

The approach taken in the current research includes both computer numerical simulation of the problem and experimental verification of the phenomena. This research was approached by first simplifying the monocoque as a hollow composite box-beam. The parameters that could potentially cause asymmetry in the response of the monocoque in left- and right-hand twisting, both before and after repairs, were then identified. The parameters predicted to have the most influence on the monocoque response were:

1. the magnitude of the constrained torsional load,
2. the location of the damage/repair zone length-wise along the structure,
3. the size and geometry of the damage/repair zone (surface area and shape), and
4. the laminate stacking sequence.

The laminate stacking sequence was chosen based on in-plane mechanical coupling characteristics and by the feasibility of laboratory manufacture. An isotropic “laminate” was also selected for use in the computer model as the control case to determine the effects of laminate mechanical coupling on the response. Because the damage is asymmetric about the monocoque xz-plane, the length-wise locations of interest were chosen based on the “proximity” to typical chassis components, such as the front suspension and the cockpit side-impact structure. Damage was simulated by cutting a hole through the laminate on one side of the beam. Repair was simulated by adding two additional unidirectional plies (called a plydrop) of $\pm 45^\circ$ with the same hole shape as the damaged counterpart to an undamaged beam specimen.

A finite element model for the beams was created in ABAQUS/CAE 6.6. Post-processing was performed by ABAQUS 6.6 and further data analysis was done in MATLAB® 2006b. Composite beams were manufactured and tested on a coordinate measurement machine (CMM). The displacement of the beam was mapped in 3D by measuring hundreds of surface points along the beam length. A structured multi-point grid was generated and compared to the corresponding finite element model displacement field. The cross-section distortion center of each beam was calculated at discrete locations along the beam length. Coupling was said to exist if the line representation of the cross-section