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Failure of bolt connection in fiber reinforced plastic component exposed to bending torque☆

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ABSTRACT

Efficient testing of bolt connections is important in truck manufacturing industry to provide high quality vehicles within short lead time. This holds in particular if the vehicle components are produced in fiber reinforced plastic composite materials, because such components are often associated with extensive test programs to obtain a complete investigation of strength, durability and effect of environmental conditions. This paper presents an experimental test setup that examines the failure strength of bolt connections exposed to bending torque. A pultruded glass fiber reinforced beam attached with steel bolts is studied in detail. Experimental results are presented to demonstrate the feasibility of the methodology, and a computational model is used to analyze the experiment and generalize the results. The conclusion is that the experiment can be computationally modeled, so that important material model parameters can be identified. Only failure strength is considered in this work, however the test setup is developed to also allow fatigue testing with repetitive loading.

1. Background

The truck industry faces currently several challenges, such as environmental and fuel consumption requirements, which require that the trucks have to become more energy efficient. This increases the interest in lightweight design solutions created by selecting advanced manufacturing materials. The interest is thus increasing to use fiber reinforced plastic composite (FRP) for loaded structural truck components. FPR has long been used in truck industry for cab interior parts and self-supporting components such as air deflectors. Also, FRP is already now considered in certain load bearing customer applications because of requirements of high performance or because of profitable increase of customer payload, for example in components such as leaf springs [1] or timber bolsters [2]. The trend is increasing use of FRP in automotive industry in general, however the forthcoming usage of FRP in truck manufacturing depends on several different aspects, such as future regulations, how the trucks are used and also the development of FRP materials and production.

The business case of the customer is considered in the design of commercial trucks, so the customer profit of lightweight solutions is compared to the cost of manufacturing and service. This means that the use of advanced materials requires well adapted design guidelines and reliable methods of predicting the component strength, because otherwise the benefit of high performance of the material is eliminated by necessary safety factors in the choice of dimensions. Adequate material models can be obtained with efficient testing, which means that predictive models are obtained with a minimum of testing. Test programs tend otherwise to be extensive to obtain a complete characterization of strength, durability and effect of environmental conditions, in particular if components made in FRP are examined (cf. [3]). Thus well defined tests with simple test specimens and distinct load cases are

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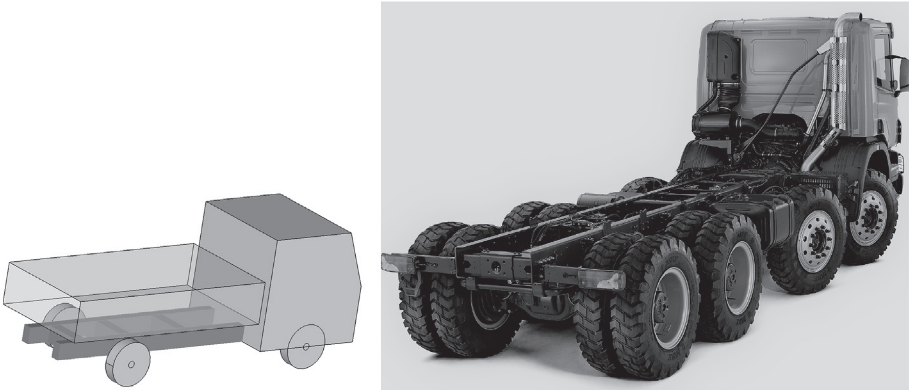

Fig. 1. Schematic truck, with bodywork and cab in light gray attached on frame members displayed in dark gray (left). Also, a truck (Scania P 380 8 × 4 XT) without bodywork to show example of a heavy duty chassis configuration (right). The usage of FRP can be consider for chassis components attached at the truck frame (e.g. fuel tanks or battery box) or body work to obtain light weight vehicles.

important. Most published research on bolt connections in FRP concentrates on aeronautical and aerospace applications [4,5], and efficient test methods for other implementations need in general to be developed further. The general advice in design of bolt connections in FRP is to avoid exposing the joint to a bending torque, but this is a severe restriction in truck design where complicated load conditions are present in general customer operation, for example in the case of truck chassis components (Fig. 1).

The bolt connection is a common joint technology in truck industry, in particular to allow efficient assembly and easy repair. Thus, experimental tests need to be performed to examine the strength of the bolt connection with respect to the loads from operation of the vehicle. A major difficulty with bolt connections in FRP compared to metal is that the clamping force of the bolts decrease over time because of stress relaxation in the FRP material [6]. As a result, the bolt connection can not rely on the friction to transfer load between components. Instead, forces are expected to be transmitted by the contact between the bolt and the bolt hole surfaces.

For FRP components there is a lack of reports in open literature treating the bending torque in bolt connections, as concluded in [4,7] and [8]. Bolt pull-through and bolt failure are the main failure modes expected due to a bending torque in a bolt connection. There are general studies where these failure modes are considered exclusively, with general results. For example it is concluded that fastener geometry and FRP material properties are important parameters of the bolt pull through strength [7] and [9], while the influence of test load rate is less pronounced [10]. To increase the predictive accuracy in specific applications, it is however necessary to perform test with more component like test specimens and authentic loading. Thus, the bending torque needs to be included in the test set-up if this is a load present in the considered application. Calculation results of a bending load case of a single bolt is provided in [11], but the proposed load case is more elementary than required by the considered application in this work, and testing of the studied load case is more demanding than the test presented in the following. The risk of bolt failure is not focus in this work since it is well presented by other research (cf. [12]). Briefly, the bolt loading is analyzed and compared with wöhler data of the specific fastener to determine if bolt failure occurs. The purpose of this paper is instead prediction of FRP damage in the bending torque load case.

The FRP composites mainly considered in automotive industry today are based on glass fiber reinforcement (GFRP, glass fiber reinforced plastic composites), carbon fiber reinforcement (CFRP, carbon fiber reinforced plastic composites) or natural fiber reinforcement (NFRC, natural fiber reinforced composites [13,14]). The choice of reinforcement in a certain component depends on several factors, such as price, strength, impact resistance, chemical resistance, flammability, fatigue properties or environmental impact. Similar factors determine the resin of the FRP. Thirdly, production methods are also crucial for the FRP material properties, and these methods are for example single component layup techniques or a continuous manufacturing processes such as pultrusion [15]. The choice of fiber, resin and production technique are dependent on each other. Pultruded GFRP members with polyester resin are considered in this work, mainly because good impact resistance, good chemical resistance and low production cost that make pultruded GFRP interesting in truck applications [16–19].

Reinforcements of the FRP component at the location of the bolt connection, such as metal inserts [20], are not considered in this work. The presented test methodology and computational model provides however also a procedure to assess the strength with respect to bending torque in bolt connections with inserts. The inserts improve the bolt connection strength and reliability significantly and preserve clamping force in the bolts over time. However the choice of using inserts needs to be considered as a trade-off between the component cost and performance.

Computational simulation of the considered experimental setup is performed with finite element calculations. The purpose is to identify critical material model parameters and thus to be able to generalize the results, as the same computational model can be applied to assess similar bolt connections. The mechanical strength is calculated with progressive damage modeling. The progressive damage modeling methodology means that a sequence of calculations is made to simulate the progression of the damage in the component when the load is increased. This is done with a damage model that considers the degradation of local constitutive properties in the material of the component. Such models are possible to implement in many commercial softwares such as in ABAQUS [21–24]. Moreover, even if the initial work on the methodology of Dugdale [25] and Barenblatt [26] focused on fracture, it