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Structural Integrity Assessment of Type IV Hydrogen Pressure Vessels: Drop Testing and Fatigue Damage Modelling

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Abstract

Hydrogen is emerging as a promising portable energy source to replace fossil fuels in the transportation sector. Compressed gaseous storage in Type IV containers, featuring polymeric liners fully wrapped by layers of carbon fibre-reinforced polymer composites, is of interest for vehicle applications. The layers are oriented in specific directions to provide the necessary strength and rigidity for both internal pressure loads and external mechanical loads. To evaluate the structural integrity and performance of hydrogen containers, a range of tests, including static, impact, and fatigue loadings, are required to ensure the safety of storage tanks under extreme conditions. This paper focuses on the assessment of damage tolerance of composite hydrogen storage tanks through numerical modelling and simulation of fatigue resistance after impact damage. The objective is to facilitate tank design, identify weaknesses, assess the resistance of the container to fatigue failure, and predict potential damage modes.

According to the CSA/ANSI HGV 2:23 standard for compressed hydrogen gas vehicle fuel containers, the pressure vessel must undergo drop testing from a height of 1.8 m in several orientations: horizontal, vertical, and titled 45° from the vertical position. After the drop test, the container must not leak or rupture within the first 3000 pressurization cycles. To assess the structural performance of a Type IV pressure vessel design, a finite element modelling methodology, validated through impact tests conducted by Carleton University and the National Research Council Canada, was applied in ABAQUS. The model was able to predict various composite failure modes, including fibre breakage, pull-out, splitting, kinking, crushing, and matrix cracking. The thickness and angle variation of helical layers at the dome region were considered. It was ensured that the design could tolerate an internal pressure of 87.5 MPa, representing 125% of the 70 MPa maximum nominal working pressure specified in the standard. The drop test was simulated using the enhanced LaRC05 failure criteria to predict impact damage. A Python script was then employed to transfer the predicted damage to a new model, where cyclic loading was applied. A progressive fatigue damage model, which accounted for the stress ratio and the effect of loading sequences, was used to ensure accurate damage accumulation prediction. The model effectively predicted the residual stiffness and strength of the material at different locations on the pressure vessel and determined the number of cycles to failure at each location based on the stress level, residual strength, and experienced loading cycles.