

## **Development and optimization of fbg smart sensors for composite structures**

*Casciaro, Emanuele (emanuele.casciaro@polimi.it), Politecnico di Milano, Italy*

*Spini, Francesca (francesca.spini@polimi.it), Politecnico di Milano, Italy*

*Bettini, Paolo (paolo.bettini@polimi.it), Politecnico di Milano, Italy*

Smart structures represent a fundamental advancement in composite structures, particularly sensorized systems developed for aeronautical applications aimed at implementing Health and Usage Monitoring Systems (HUMS). Among the various sensing technologies considered for these structures, optical fibers have emerged as a highly promising solution. Their main advantages include low invasiveness, reduced weight and immunity to electromagnetic interference. The possibility of placing sensors that enable local measurements at any point within a structure, including through its thickness, and with a desired orientation would represent a significant advantage for monitoring strategies. Such solutions are currently under investigation and development. In this work, the integration of Fiber Bragg Grating (FBG) sensors into composite materials is considered. This solution, however, presents several challenges related both to sensor positioning along complex geometric paths and to the risk of optical fiber damage or fracture during manufacturing. Indeed, embedding of optical fibers often results in handling difficulties, misalignment and fiber breakage during lay-up and curing operations. To overcome these limitations, a pre-assembled smart sensing solution, called quick-pack, was developed. The smart sensor consists of multiple thin layers, including neat epoxy resin layers and epoxy resin reinforced with glass fiber fabric, within which the optical fiber is embedded prior to integration into the composite structure. This configuration enhances sensor robustness and handling while facilitating accurate positioning of FBG sensors along predefined paths, thus improving measurement repeatability and reliability. However, the effectiveness of the quick-pack embedment is influenced by the processing conditions adopted during the production, requiring a dedicated investigation of the integration strategy. In particular, the effect of partial epoxy resin crosslinking on the adhesion and peeling behaviour of the quick-pack within the composite laminate was examined. Experimental results demonstrate that improved peeling performance is obtained when partially crosslinked quick-pack sensors are employed rather than fully cured ones. When a partially cured quick-pack sensor is embedded into the composite laminate, resin crosslinking continues during the curing cycle of the composite, resulting in a co-curing mechanism that promotes improved interfacial bonding. Moreover, the degree of epoxy resin crosslinking must be carefully controlled. Indeed, low degree of crosslinking can cause optical fiber displacement from the predefined path, compromising sensor positioning and measurement accuracy. To support the identification of an optimal curing conditions, a detailed study of the epoxy resin curing kinetics was performed through Differential Scanning Calorimetry (DSC). Both model-based and model-free kinetic approaches, such as Kamal-Sourour and nth order, were used to monitor the evolution of crosslinking and study the degree of cure as a function of time and temperature. In addition, gel point identification was performed to exclude curing degrees characterized by insufficient polymer network formation, which could result in optical fiber displacement from the intended geometric path. The optimal degree of crosslinking can be therefore determined by combining peeling tests with thermal and rheological analyses, enabling a correlation between interfacial mechanical performance and resin curing behaviour. Finally, quick-pack sensors with embedded FBG sensors cured at different degrees of crosslinking were tested under ambient temperature storage conditions (25°C) and at 125 °C. The aim of these tests was the determination of the influence of ambient storage during the embedding process, as well as the evolution of resin crosslinking and viscoelastic behaviour at temperatures representative of typical composite manufacturing cycles.