University of Salerno
Department of Civil Engineering

PhD course in
Risk and Sustainability in Civil, Architectural and Environmental Engineering Systems

PhD Thesis title:

Safeability of a beam-to-column adhesive connection: experimental investigation and modeling

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Cycle XXXIV (aa 2018-2021)

Synthesis

Fibre Reinforced Polymer (FRP) materials are appealing as alternative to traditional construction materials due to their high tensile strength, excellent resistance to aggressive environments, high strength to weight ratio, simple and rapid installation time. Also, due to their low maintenance requirements, these materials offer a promising alternative for the development of more durable and sustainable structures. The connections in GFRP structures are deemed to be essential in providing the required load-carrying capacities.

The connection technology for pultruded GFRP profiles presents numerous challenges due to the brittle and anisotropic nature of the material. GFRP profiles are usually connected via bolting, adopting the design rules for similar steel connections, but in the last decade the adhesive technique has gained more and more interest.

International Standards stipulates that bonded connections should not be allowed for primary load bearing components. Their use is permitted only in combination with or as a backup for bolted connections. The main reason for the prohibition of bonded connections is lack of knowledge about and experience with the performance of such connections. Hence, there is need for research on bonded connections in order to understand their behavior, in terms of strength and stiffness, and to assess their performance vis-a-vis similar bolted connections. The knowledge thus gained can be used by designers to safely design composite structures with bonded connections, provided that it can be demonstrated to be more advantageous than using bolted connections.

Theoretically, there are reasons to believe that bonded connections can be superior to bolted connections in FRP composite structures.

In fact, compared with the traditional mechanical assembly technologies (e.g., bolted, pinned or riveted methods), adhesive bonding has a lot of advantages. First of all, nearly all types of materials, including composite materials in particular, can be bonded by adhesives. Secondly, adhesive bonding technology makes bonded structures light in comparison to other assembly technologies (e.g. mechanical fasteners). Thirdly, due to the characteristic of making no holes in the surface prior to bonding, stress concentration can be decreased compared to other methods such as bolting and/or riveting.

However, as confirmed by current literature, the mechanical response of structural adhesives in general and that of the bonded joints, in particular, is significantly dependent on several factors such as the temperature (both high and low values) and the moisture which may limit the applicability of structural adhesives. The environmental temperature may exceed the glass transition temperature (T_g) of the adhesive formulation entailing relevant changes in its properties, determining a transition from a hard to a rubbery behaviour, thus compromising its specific application. Due to different environmental parameters experienced by the assembled structures during the use, among which the temperature values, the adhesive can be naturally subjected to a delay or increase in the curing degree. This can lead to adverse or positive changes in strength and stiffness. The speed and extent of the changes depend on the magnitude and duration of the temperatures experienced by the adhesive.

The temperature and moisture may also produce effects on the long-term properties of the adhesives. Within this framework, several studies have been carried out on the durability of epoxy adhesives.
Within this framework, in order to further encouraging the spread of bonded connections, with particular regard to the field of civil engineering where the beam-to-column is the most common connection, the scopes of the present research activity are: 1) to find the most accurate geometry for such a connection; 2) to evaluate the fracture energy (in function of the hygrothermal durability) of epoxy resins which are in general the most suitable ones for bonding each other pultruded profiles; 3) to evaluate the strength and stiffness by the approach of "testing by testing" in order to create a large database that could be useful when building predictive mechanical models; 4) to try to overcome some negative peculiarities of such a connection like the brittle failure and the not repairability.

PART I: The mechanical behaviour of a full adhesive beam-to-column connection
Object of this Part I of the thesis is the study of the global behaviour of a full adhesive beam-to-column connection from both an experimental and numerical point of view. More in details, the role played by the hygro-thermal aging, by the bonded area extension and by the load condition is investigated. For what concerns the study of the aging influence, a wide preliminary experimental study about the durability of epoxy resins, suitable for bonding pultruded profiles each other, is presented (Chapter 1). This topic was developed in collaboration with Professor Liberata Guadagno and Dr. Carlo Naddeo of the Industrial Department of the University of Salerno.
Furthermore, the experimental investigation related to the global mechanical behaviour of the full scale beam-to-column adhesive connections presented in the Chapter 3 was developed in collaboration with Dr. Giulia Carozzi of the TopGlass Industries.
The first step is the study of the hygro-thermal durability of two commercial epoxy resins, suitable for civil engineering applications, respect to the immersion in tap water and sea water for a period of fifteen months at the temperature of 30°C. To this scope a wide experimental program was developed comprising both End Notch Failure (ENF) tests on the adhesive samples (adherent in glass fiber reinforced polymer, GFRP) for evaluating the pure fracture energy in Mode II of the resins and the water absorption and desorption tests for resins and GFRP materials.
Parallel to the experimental program, analytical simulations, based on the application of the Fick's law, were developed in order to simulate the water uptakes experimentally observed.
In view of a safe design of a bonded joint, limiting its behaviour to only the elastic field, a lower fracture energy value is presented in relation to the classical one.
More in detail, a Finite Element Model (FEM), by using the commercial Abaqus code, was built. It is capable of perfectly describing, on one hand, the End Notch Failure (ENF) test used to evaluate fracture energy in mode II as requested by current standards, while on the other, to evaluate the stiffness of the elastic and softening stages in the case of ageing.
The experimental program involved the realization and laboratory testing of thirty full scale glass fiber reinforced polymer (GFRP) connections composed of a square hollow section, acting as a column, connected to a built-up beam made of two U-profiles by means of the epoxy resin. This

chapter studies the influence of several parameters, such as the extension of the bonded area, the load condition and hygro-thermal aging on the global mechanical response of beam-to-column adhesive joints. The beam-column assembly formed an L-shaped frame tested by applying a point load at the beam free end (bending) and close to the column (shear), while the column was fixed at its base. Furthermore, five different bonded area configurations were considered and tested, with two different aging conditions being taken into account: conditioning in Tap Water and Sea Water for one year at the constant temperature of 30°C.
Based on a large database there are presented two mechanical models with closed form solutions in order to predict both the strength and the stiffness of such a connection. The comparison with experimental results available in the literature made it possible to verify the effectiveness of the proposed formulation which involves only a few geometric and mechanical parameters as better described below.

PART II: Hybrid GFRP/steel connection suitable for fiber reinforced composite materials
Object of this Part II of the thesis is the study of an innovative dissipative hybrid beam-to-column connection between pultruded profiles suitable for large scale structures.
The joint was firstly designed and produced, an after tested trough a wide experimental program composed of more than seventy full scale specimens.
This topic was developed in collaboration with Professor Luciano Feo from the University of Salerno and with Professors Raffaele Landolfo and Mario D'Aniello form the University of Naples "Federico II".
Thanks to the excellent and encouraging results obtained, the inventors decided to apply for a national/international patent. Because of the procedure is still in progress, the author of this Thesis cannot published any drawing or result about the invention. Consequently, a general description of the invention is only presented underlying the main features.
Based on the full adhesive beam-to-column connection investigated form an experimental and mechanical point of view in the Part I of this Thesis, a companion hybrid connection was designed, produced and tested. The concept behind this new connection is that fiber reinforced members have to be bonded (in order to preserve the fiber continuity) to steel ones while steel members are bolted each other as usually happened in practice.
The two main scopes of this innovative connection are: 1) to furnish ductility to the system by the introducing of a steel core; 2) to localize the failure in a specific steel element (like a fuse) which could be easily repaired and/or substitute with a new one anticipating and then preventing the failure in the adhesives (which are not easily repairable as is well known).
The connection was tested trough a wide experimental program conducted at the Strength Laboratory of the University of Salerno comprises of more than seventy full scale specimens. The quasi-static tests in displacement control were performed using an universal testing machine. The key parameters till now investigated were: 1) the extension of the bonded area between GFRP elements and steel ones; 2) the thickness of the "fuse".
The results till now obtained are encouraging and the experimental program will continue in the next few months by performing cyclic tests.