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Novel hybrid FRP tubular columns for sustainable mining infrastructure: Recent research at University of Wollongong

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ABSTRACT

This paper introduces, for applications in the mining industry, an innovative hybrid column form which consists of an inner steel tube, an outer fibre-reinforced polymer (FRP) tube and an annular concrete infill between them. The two tubes may be concentrically placed to produce a section form more suitable for columns, or eccentrically placed to produce a section form more suitable for beams. The FRP is combined with steel and concrete in these hybrid structural members in such a way that the advantages of FRP are appropriately exploited while its disadvantages are minimized. As a result, these hybrid members possess excellent corrosion resistance as well as excellent ductility and seismic resistance. This paper summarizes existing research on this new form of structural members, and discusses their potential applications in mining infrastructure before presenting a summary of the recent and current studies at University of Wollongong (UOW) on their structural behaviour and design.

1. Introduction

In recent years, fibre-reinforced polymer (FRP) composites have found increasingly wide applications in civil engineering, both in the retrofit of existing structures and in new construction. FRP composites possess several advantages over steel, including their high strength-to-weight ratio and good corrosion resistance. As a result, the use of FRP composites as externally bonded reinforcement for the retrofit of structures has become very popular in recent years [1]. These same advantages can also be exploited in new construction, and indeed a large amount of research around the world is currently under way examining the performance of various forms of structures made of FRP composites alone (i.e., all FRP structures) or FRP composites in combination with other materials (i.e., hybrid structures) [2,3]. Examples include FRP bridge decks, concrete filled FRP tubes as columns and piles, and FRP cables.

Compared with the two primary traditional structural materials, namely steel and concrete, FRP composites also have some disadvantages. These include their relatively high cost, linear–elastic–brittle stress–strain behavior, low elastic modulus-to-strength ratio, and poor fire resistance. In retrofit applications, cost savings arise from a number of aspects that offset the higher material cost, but this is harder to achieve in new construction at present. The low elastic modulus-to-strength ratio is not critical in retrofit applications as the FRP is generally used to resist tension. The poor fire performance is also not an acute problem in retrofit applications either because the structure is in the open space (e.g., bridges) or because the FRP is not required to make any contribution to structural resistance during a fire. When FRP composites are deployed in new construction, the consequences of their weaknesses need to be minimized as in retrofit applications. Based on these considerations, it may be concluded that the successful application of FRP composites in new construction requires the following three criteria to be met [2,3]: (a) cost effectiveness at least in terms of a life-cycle cost assessment; (b) FRP to be used in areas subject to tension as much as possible; (c) fire resistance to be non-critical. It should be noted that the third criterion is easily met for bridge structures and other outdoor structures, while the first two requirements very often mean that FRP composites should be used in combination with other materials to form hybrid structures. It is apparent that the area of hybrid structures should be a major research focus in the use of FRP composites in new construction. Within the area of hybrid structures, the aim shall be to optimally combine FRP with traditional structural materials such as steel and concrete to create innovative structural forms that are cost-effective and high-performance [2,3]. To this end, simple duplications of existing structural systems are often inadequate.

This paper introduces, for applications in the mining industry, a new type of FRP–concrete–steel structural member developed at The Hong Kong Polytechnic University, in which the three

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constituent materials are optimally combined to achieve several advantages not available with existing columns. The rationale and advantages of this new form of structural members are explained, and their potential applications in mining infrastructure are discussed before the recent and current studies at University of Wollongong (UOW) on their structural behavior and design are summarized.

2. Section forms and advantages

This new type of structural members (Fig. 1), proposed by Prof. JG Teng at The Hong Kong Polytechnic University, is referred to as hybrid FRP–concrete–steel double-skin tubular members (DSTMs) or hybrid DSTMs for brevity [2,3]. A hybrid DSTM consists of an outer tube made of fibre-reinforced polymer (FRP) and an inner tube made of steel, with the space between filled with concrete. The two tubes may be concentrically placed (Fig. 1a and b) to produce a section form more suitable for columns, or eccentrically placed to produce a section form more suitable for beams (Fig. 1c and d). In hybrid DSTMs, the FRP tube offers mechanical resistance primarily in the hoop direction to confine the concrete and to enhance the shear resistance of the member. Hybrid DSTMs may be constructed in situ or precast, with the two tubes acting as the stay-in-place form. The sections of the two tubes may be both circular (Fig. 1a and c), rectangular (Fig. 1d), or in another shape; they may also have shapes different from each other (Fig. 1b). Shear connectors need to be provided between the steel tube and the concrete, particularly in beams, but are generally not needed for the FRP tube which is normally designed to have only a small longitudinal stiffness.

The most important advantage of hybrid DSTMs is their excellent corrosion resistance, as the FRP tube is highly resistant to corrosion while the steel tube is protected by the FRP tube and the concrete. The other main advantages of hybrid DSTMs include: (1) excellent ductility, as the concrete is well confined by the two tubes and outward local buckling of the steel tube is constrained by the concrete; (2) a high strength/stiffness-to-weight ratio as the inner void largely eliminates the redundant concrete; (3) ease of construction, as the two tubes act as a permanent form for casting concrete, and the presence of the inner steel tube and the concrete allows easy connection to other members. Teng et al. further discussed the rationale and advantages of hybrid DSTMs [3].

3. Comparison with existing column forms

3.1. Comparison with hollow RC columns

Among the existing forms of columns which may be replaced by hybrid DSTMs, hollow RC columns are the most cost-effective. Hollow RC columns have been widely used because of their high bending resistance coupled with reduced weight. A detailed cost comparison between a hybrid DSTM and a hollow RC column was undertaken in 2006 and Teng et al. reported in detail [4]. This comparison indicates that the construction costs of hybrid DSTMs and hollow RC columns are similar, but the hybrid DSTM has a larger section capacity than the hollow RC column when the axial force is reasonably high but the two sections have similar section capacities when bending dominates the behavior. Besides the load capacity, it should also be noted that hybrid DSTMs possess two important advantages over hollow RC columns: excellent corrosion resistance and excellent seismic resistance.

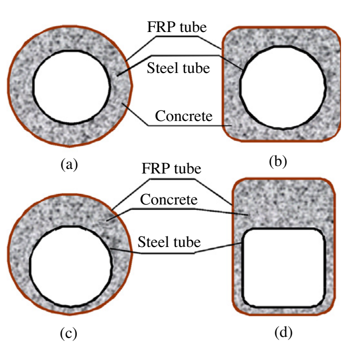

Fig. 1. Typical sections of hybrid DSTMs.

3.2. Comparison with other column forms

Steel–concrete DSTMs with both skins made of steel have been used in construction and have been intensively researched. Such columns have a higher initial construction cost than hollow RC columns for the same structural performance, similar to the well-known fact that concrete-filled steel tubes are more expensive than RC columns. FRP–concrete DSTMs with two FRP tubes have also been explored but the use of FRP instead of steel for the inner tube does not lead to any significant advantage but a number of significant disadvantages (e.g., higher cost, reduced stiffness to confine concrete, brittle failure in tension).

Intensive recent research has been conducted on concrete-filled FRP tubes (CFFTs) (i.e., with a solid concrete core) as columns and piles. There have also been some field applications of CFFTs. If excellent durability is the overriding criterion, CFFTs are a possible choice but they are significantly more expensive than RC columns because the FRP tube needs to be thick and to be provided with both longitudinal and hoop fibres. If the FRP tube is not sufficiently thick, premature buckling under compression will considerably compromise its confinement of the concrete core. Even if buckling does not occur, adverse interaction exists between axial compression and hoop tension in such a tube. A hybrid DSTM may be seen as a CFFT with its FRP tube split into an outer FRP tube containing the hoop fibres and an inner FRP tube containing the axial fibres which is then replaced by a much stiffer and much more ductile steel tube. The inner void can also be used for the passing of service ducts. It needs to be emphasized that the FRP tube in a DSTM should generally be quite thin, as its main purpose is to enhance the ductility of the column. Hybrid DSTMs offer many advantages over CFFTs: (a) better confinement of concrete by the FRP tube which contains fibres predominately oriented in the hoop direction; such a tube is mainly subjected to hoop tension and does not buckle under axial straining as has been observed in numerous existing tests of FRP-confined concrete columns; (b) ductile failure in bending as the steel inner tube acts as the longitudinal reinforcement; and (c) savings in cost as the FRP tube is used as a confining device for ductile column response and does not need to be thick.

4. Potential practical application

Because of their excellent corrosion resistance, hybrid DSTMs are most suitable for use in structures which are likely to be exposed to a harsh environment (e.g., coastal structures and underground structures). Hybrid DSTMs can be used as compression members, such as piles, various towers (e.g., wind turbine towers and electricity transmission towers) and other similar structures. In longwall mining, hybrid DSTMs can be used in a roof support system for maingates and/or tailgates. The excellent structural performance of hybrid DSTMs makes them a promising alternative to existing systems (e.g., Fig. 2) [5,6]. The presence of an inner void in hybrid DSTMs is also an important advantage which can be exploited in mining applications. The inner void can be used for the passing of service ducts or for ventilation, so that hybrid DSTMs