Structural Behavior of Hybrid FRP-Concrete-Steel Double-Skin Tubular Columns

T. Yu, Y.L. Wong, J.G. Teng, and S.L. Dong

ABSTRACT

In this paper, a new hybrid FRP-concrete-steel double-skin tubular member recently proposed by the third author is discussed, with the emphasis being on its potential as key lateral and vertical load-resisting members in structures located in seismically active regions. In this new structural member, the three constituent materials are optimally combined: the outer tube is made of fibre-reinforced polymer (FRP), the inner tube is made of steel, and the space in-between is filled with concrete. While such a member may be used as a beam, its advantages are most obvious when used as a column so this new member may also be conveniently referred to as a hybrid FRP-concrete-steel double-skin tubular column (DSTC). A series of preliminary tests have recently been conducted, in which the concentric compressive behaviour and the flexural behaviour of the member were investigated. The test results showed that this new hybrid member exhibits good ductility and energy dissipation capacity.

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INTRODUCTION

Seismic design codes together with their underlying philosophy have been continuously improved with the development of knowledge on the seismic damage and collapse of existing structures during significant earthquakes. Some examples of this development can be found in the changes of the seismic design philosophy in the USA after the 1971 San Fernando earthquake and the revision of the Building Code in Japan after the 1968 Tokachi-Oki and the 1978 Miyagi-ken Oki earthquakes (Teng et al. 2002). The advancement of seismic design codes often leads to a stricter requirement on the ductility, shear and flexural capacities, and connection details of structural members. As a result, structures designed according to the latest codes often end up with a large amount of reinforcement at beam ends, column ends, and beam-column joints in reinforced concrete (RC) structures, leading to steel congestion and possibly poor concrete quality in these members (Lin and Lee 2003). In order to solve this problem, many ideas have been explored, such as the use of high-workability concrete and high-performance steel reinforcement (Lin and Lee 2003) as well as the development of composite structural configurations that utilize the advantages of different materials.

Columns are considered as critical members in moment-resisting structural systems. Their failure may lead to a partial or even a total collapse of the whole structure. Therefore, it is important to improve the ductile deformation capacity and energy dissipation capacity of columns so that the entire structure can endure severe ground motions and dissipate a considerable amount of seismic energy. In recent years, composite concrete-filled steel tubes (CFSTs) have become increasingly popular as columns in braced and unbraced frames, as they have the advantages of ductile behaviour as a result of confinement to concrete by the steel tube and delayed local buckling of the steel tube due to the support from concrete, improved damping behaviour in comparison to traditional steel frames, ease for construction as the steel tube serves also as the permanent form, and a high strength-to-weight ratio (Hajjar 2000, 2002; Varma et al. 2002).

Fibre reinforced polymer (FRP) is composed of stiff fibres embedded in a resin matrix. As a new construction material, it has gained its popularity over the past decade as a jacketing material in the retrofit of existing RC columns to achieve improved seismic resistance (Teng et al. 2002; Seible et al. 1997). FRP jackets (or wraps) have been shown to significantly enhance the shear and flexural strengths, ductility, and energy dissipation capacity of columns (Teng et al. 2002).

The application of FRP tubes in new construction has also been explored by many researchers (Fam and Rizkalla 2001; Mirmiran and Shahawy 1997). In particular, FRP tubes are used as the stay-in form for constructing concrete-filled FRP tubular columns, with or without an inner void. Such FRP tubes generally have both axial fibres to provide longitudinal reinforcement and hoop fibres to provide confinement to concrete. Concrete-filled FRP tubes (CFFTs) have almost all the advantages of concrete-filled steel tubes in resisting seismic loading. In addition, FRP tubes are very light and do not suffer from the corrosion problem of steel tubes. Concrete-filled FRP tubes also have their own disadvantages, including the high material cost of FRP, a low modulus-to-strength ratio and poor fire resistance.

A variation of the concrete filled tubular column is the double-skin tubular column (DSTC), consisting of two generally concentric tubes with the space between filled with concrete. To the best knowledge of the authors, such double-skin tubes were first reported in late 1980s (Shakir-Khalil and Iollo 1987). Since then, much research has been conducted on these columns, both on double-skin steel tubular columns (Shakir-Khalil 1991; Wei et al. 1995; Yagishita 2000; Zhao et al. 2002; Tao et al. 2003) and double-skin FRP tubular columns (Fam and Rizkalla 2001). The inner void
reduces the column weight without significantly affecting the bending rigidity of the section and allows the easy passage of service ducts.

NEW HYBRID DSTC

The new hybrid FRP-concrete-steel double-skin tubular structural member was recently proposed by the third author of this paper (Teng et al. 2004). The new hybrid member consists of a steel tube inside, an FRP tube outside and concrete in between (Figure 1). The inner void may be filled with concrete if desired. The FRP tube is provided with fibres which are predominantly oriented in the circumferential direction to provide confinement to the concrete. The new hybrid member is an attempt to combine the advantages of all three constituent materials and those of the structural form of DSTCs, so as to achieve a high-performance structural member.

This new structural member is believed to have good seismic performance, as well as many other advantages, as discussed below. While such a member may be used as a beam, its advantages are most obvious when used as a column so this new member may also be conveniently referred to as a hybrid FRP-concrete-steel double-skin tubular column (DSTC).

Ductility and Energy Dissipation Capacity

Under seismic attacks, the ductility and energy dissipation capacity of a column are the major concerns. Confinement to concrete is an effective means of improving the ductility of a column in which concrete is a main material. It has been demonstrated by extensive research that concrete confined by a steel tube outside can exhibit much better ductility compared with unconfined concrete, either under monotonic loading (see Figure 2) or cyclic loading. Extensive research on FRP-confined concrete has shown that FRP tube confinement to concrete can also significantly enhance the strength and strain capacity of concrete, although the stress-strain behaviour of steel-confined concrete differs from that of FRP-confined concrete (see Figure 2).
Some previous research has revealed that a concentric hole in the concrete section may decrease the confining effect of the FRP tube on the concrete (Fam and Rizkalla 2001). In the present hybrid DSTC, the steel tube inside provides compensation for the inner void, as indicated by the test results of Fam and Rizkalla (2001) for double-skin tubular FRP columns and Zhao et al. (2002) for double-skin tubular steel columns.

In conventional CFSTs and CFFTs, the axial stiffness and strength of the outer tube are substantial and important. The considerable axial stiffness leads to a large axial compressive stress on the tube by either direct end loading or by friction between the concrete and the tube. As the outer tube is generally loaded in hoop tension by the expansion of the concrete, the FRP tube is generally subjected to a combined tension-compression stress state. Lateral expansion of the FRP tube through the Poisson’s effect reduces the effectiveness of confinement to the concrete, and in addition, local buckling of the outer tube becomes an important failure mode. In the new hybrid member, the inner steel tube acts as the longitudinal reinforcement, while the FRP tube outside is provided with fibres predominantly oriented in the circumferential direction to provide confinement only. The FRP tube outside in the new hybrid member thus has a much lower axial stiffness and the effect of Poisson’s ratio on the lateral expansion of the FRP tube is almost negligible.

**Other Advantages of the New Hybrid DSTC**

Compared with CFSTs and double-skin tubular steel columns, this new DSTC is highly resistant to corrosion as the FRP tube outside is corrosion-free and the steel reinforcement is well protected by the concrete and the FRP tube from environmental attacks. Compared with CFFTs and double-skin FRP columns, the new DSTC is cheaper to build, has a more ductile behaviour and can be much more easily connected with other structural members because the existing connection technology for CFSTs can be used with the new hybrid DSTC due to the presence of the inner steel tube. In addition, the new hybrid DSTC is expected to possess good flexural and shear strengths and to be less susceptible to local buckling problems.
However, this new hybrid structural member is still in its infancy and its expected advantages need to be demonstrated both experimentally and theoretically. Important behavioural aspects include monotonic and cyclic concentric axial compressive behaviour, beam-column behaviour, and behaviour under combined axial loading and cyclic lateral loading. Some preliminary experimental work has recently been carried out on this new hybrid DSTC, which includes stub column tests designed to evaluate the monotonic concentric compressive behaviour and four-point bending tests forming part of the experimental program designed to evaluate the behaviour of this member under combined axial and lateral loading.

**CONCENTRIC COMPRESSIVE BEHAVIOR**

Six DSTC specimens with three different configurations were prepared and tested under concentric compression. The results are summarised here but a more detailed report is available elsewhere (Teng et al. 2004). The columns all had an outer diameter of 152.5mm, a height of 305mm, and the same steel tube inside. They were provided with GFRP tubes of different thicknesses outside, which had fibres only in the hoop direction. Table 1 shows a summary of the test specimens.

Tensile tests on steel coupons were conducted. It was found that the steel tube had a yield stress of 352.7MPa, an ultimate tensile strength of 380.4MPa and a Young’s modulus of 207.28 GPa. The FRP tubes were prepared by the wet lay-up process; the FRP used had a nominal thickness of 0.17mm per ply, a tensile strength of 2300MPa and a Young’s modulus of 76GPa based on this nominal thickness according to the manufacturer’s data. The elastic modulus, compressive strength and strain at peak stress of the concrete averaged from three concrete cylinder tests (152.5 mm x 305 mm) are 30.2 MPa, 39.6 MPa and 0.002628 respectively.

During the test, all specimens exhibited a smooth load-displacement curve until failure took place, when the outer GFRP ruptured and the load began to drop. The test results of the 6 specimens are summarized in Table 2. In this table, $P_{co}$ is equal to the unconfined concrete strength times the area of the annular concrete section (=543.5 kN), while $P_s$ is equal to the average ultimate load from three axial compression tests on hollow steel tubes (=273.8 kN). Therefore, the ultimate load of the hybrid column is 817.3 kN if the constituent parts do not interact and the confinement effect of the GFRP tube is negligible. The ultimate load of the hybrid column from the test is denoted by $P_c$, while the ultimate strain is denoted by $\varepsilon_u$ at the attainment of $P_c$. The axial load-axial strain curves of the six DSTCs are shown in Figure 3.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>GFRP tube</th>
<th>Steel tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS1A, DS1B</td>
<td>1 ply</td>
<td>Outer Diameter = 76.1 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness = 3.2 mm</td>
</tr>
<tr>
<td>DS2A, DS2B</td>
<td>2 plies</td>
<td></td>
</tr>
<tr>
<td>DS3A, DS3B</td>
<td>3 plies</td>
<td></td>
</tr>
</tbody>
</table>

From Table 2, it can be seen that the two specimens with a one-ply FRP tube have approximately the same load capacity as the sum of those of the concrete and the inner steel tube,
which shows that the confinement on concrete by the two tubes has little effect on its ultimate strength when a thin FRP tube is used. However, the load capacities of DSTCs with a two- and three-ply FRP tube outside exceed the sum of the ultimate strengths of the two constituent parts by a considerable amount: 27% for the DSTCs with a two-ply FRP tube and 48% for the DSTCs with a three-ply FRP tube. It can also be seen from Figure 3 that the DSTCs with a two-ply FRP tube and those with a three-ply FRP tube show a bilinear load-strain curve, while the DSTCs with a one-ply FRP tube show approximately elastic-perfectly plastic behaviour. All the specimens displayed much larger ductility than that of unconfined concrete. The ultimate axial strains are 5.53, 7.69 and 8.96 times that of the unconfined concrete for one-, two- and three-ply FRP tubes respectively (Table 2).

Table 2. Test results of DSTCs

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( P_c ) (kN)</th>
<th>Average ( P_c ) (kN)</th>
<th>( P_c/(P_{co}+P_s) ) (MPa)</th>
<th>( \varepsilon_u \times 10^{-6} )</th>
<th>Average ( \varepsilon_u \times 10^{-6} )</th>
<th>( \varepsilon_u / \varepsilon_{co} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS1A</td>
<td>793.8</td>
<td>811.5</td>
<td>0.99</td>
<td>14208</td>
<td>14542</td>
<td>5.53</td>
</tr>
<tr>
<td>DS1B</td>
<td>829.3</td>
<td>811.5</td>
<td>0.99</td>
<td>14875</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS2A</td>
<td>1044.2</td>
<td>1034.5</td>
<td>1.27</td>
<td>22000</td>
<td>20204</td>
<td>7.69</td>
</tr>
<tr>
<td>DS2B</td>
<td>1024.8</td>
<td>1024</td>
<td>1.27</td>
<td>18417</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS3A</td>
<td>1214.0</td>
<td>1208.0</td>
<td>1.48</td>
<td>23416</td>
<td>23541</td>
<td>8.96</td>
</tr>
<tr>
<td>DS3B</td>
<td>1201.9</td>
<td>1208</td>
<td>1.48</td>
<td>23666</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Axial load-axial strain behaviour of DSTCs
FLEXURAL BEHAVIOR

A series of four-point bending tests were carried out on the new hybrid structural member. In total, six specimens were prepared and tested. The specimens all had an outer diameter of 152.5mm and a length of 1500 mm. They covered different unconfined concrete strengths, different thicknesses of the steel tube, and different thicknesses of the FRP tube. Details of the specimens are summarized in Table 3. The test set-up is shown in Figures 4 and 5.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>FRP</th>
<th>Steel</th>
<th>Concrete strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSB1A</td>
<td>1 ply</td>
<td>Outer Diameter = 76.1 mm Thickness = 2.7 mm</td>
<td>38.2MPa</td>
</tr>
<tr>
<td>DSB2A</td>
<td>2 plies</td>
<td>Outer Diameter = 76.1 mm Thickness = 3.2 mm</td>
<td></td>
</tr>
<tr>
<td>DSB1B</td>
<td>1 ply</td>
<td>Outer Diameter = 76.1 mm Thickness = 4.3 mm</td>
<td>35.5MPa</td>
</tr>
<tr>
<td>DSB2B</td>
<td>2 plies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSB1C</td>
<td>1 ply</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSB2C</td>
<td>2 plies</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Details of the bending test specimens

Figure 4. Dimensions of bending test set-up

The instrumentation included 16 strain rosettes (8 per section) which were evenly distributed around the circumferences of Sections 1 and 2 (Figure 4), five LVDTs which were installed at
Sections 1, 2 and 3 (Figure 4) and the two loading sections (Figure 5 (a)) to measure deflections, and two LVDTs at each end of the specimen to measure the slips between the concrete and the steel tube and between the concrete and the FRP tube (Figure 5 (b)). Two load cells were used to measure the loads acting at the two loading points (Figure 5 (a)). The test data were collected by a data logger.

All bending test specimens except DSB1A exhibited a smooth load-deflection curve (Figure 6). However, during the test of DSB1A, there was a sudden load drop accompanied by a loud noise at a load $P=26.1\text{kN}$ at each loading point and a mid-span deflection of 54.1mm. All tests were terminated due to the headroom limitation of the loading frame (at a mid-span deflection of about 150mm). At a load level of about 15% the ultimate load, flexural cracks were initiated. New cracks and extension of existing cracks were observed upon further loading. Two major cracks were always found right below or very close to the two loading points, while other less prominent cracks were randomly distributed within and outside the pure-bending region of the specimen (Figure 7). The early occurrence and large widths of cracks observed in these tests indicate that if the hybrid member is used to resist bending only, some improvements are required, including the addition of longitudinal fibres in the outer GFRP tube. It should be noted that the present tests were designed to understand the flexural behaviour of this hybrid ember as part of the overall picture of the behaviour of this member as a beam-column, so the early cracking and large crack widths are not necessarily of great concern if the hybrid member is used as a column subject to a significant axial load.
Figure 7. Specimen at the end of a test

Figure 6 shows the load-deflection curves of the specimens for the mid-span point. It is evident that all six specimens showed good ductility. As the specimens did not collapse at the end of the test, they can be expected to possess a higher level of ductility than is indicated by these curves. It is also evident that the thickness of the GFRP tube has little effect on the load capacity of the member, as each of the three specimen pairs with a 1-ply and a 2-ply GFRP tube respectively exhibited similar load-deflection behaviour. As expected, the thickness of the inner steel tube has a significant effect on the ultimate load of the member.

A careful study into the LVDT readings at the ends of specimen DSB1A revealed that during this test, there was a sudden increase in the slip between the concrete and the steel tube at the onset of the sudden load drop of this specimen (Figure 6). It is therefore believed that the sudden slip increase between the concrete and the steel tube led to at least a partial loss of the composite action between these two components and thus a sudden load drop. This indicates that an improvement of the bond between the concrete and the steel tube may be needed.

CONCLUSION

A new hybrid structural member recently proposed by the third author of this paper has been discussed, with the emphasis being on its potential as key lateral and vertical load-resisting members in structures located in seismically active regions. The new member consists of a steel tube inside, an FRP tube outside and concrete in between. While this hybrid member may be used as a beam, its advantages are most obvious when used as a column so this new member may also be conveniently referred to as a hybrid FRP-concrete-steel double-skin tubular column (DSTC). A series of stub column tests and four-point bending tests were carried out on the new hybrid member, the results of which have been introduced in this paper. Based on the test results, the following conclusions can be drawn:

1) This new hybrid structural member possesses good ductility and good energy dissipation capacity. When subjected to concentric compression, the concrete sandwiched between the two tubes may achieve significant enhancement in both strength and ductility over unconfined concrete. According to Teng et al. (2004), the concrete in a typical hybrid DSTC may be confined as effectively as that in an FRP-confined solid concrete cylinder.
2) The new hybrid member shows good ductility under four-point bending, although significant cracks will occur early in the loading process. Longitudinal fibers may be required in the outer GFRP tube if the new hybrid member is to be used to resist bending only. In addition, there may be a need to improve the bond between the concrete and the steel tube, such as through the use of mechanical shear connectors to prevent possible premature slips as observed in one of the beam tests presented in the paper.

3) Further tests, including eccentric compression tests, combined axial and cyclic lateral loading tests and shaking table tests, should be carried out in the future to develop a more complete understanding of the seismic performance of the new hybrid member and structural systems based on this new member form.

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