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Flexural Behaviour of Hybrid Double-Skin Tubular Beams Having Perfobond Hoop Shear Connectors

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Abstract: *The load-deflection behavior of hybrid fiber-reinforced polymer (FRP)-concrete-steel double-skin tubular beams (DSTBs) is quite ductile, but there may be considerable amounts of slippage between the concrete and the inner steel tube. To improve the bond performance between the concrete and the steel in heavy duty composite beams, Perfobond (PBL) shear connectors are commonly used. PBH was proposed based on the researches of PBL shear connectors The PBH shear connector consists of stirrup and stiffening ribs, which allow the steel box and concrete to work together. In this study Perfobond hoop shear connectors (PBH) provided in hybrid DSTBs for the first time. This study presents a experimental study aimed to developing a good understanding about the behavior of new hybrid double skin tubular beams with PBH shear connectors comparing with PBL shear connectors, also investigates the flexural performance of hybrid DSTBs having different cross-sections.*

Key Word: *Double-skin tubular beams, Slippage, Perofobond Hoop Connector.*

I.INTRODUCTION

1.1 General

Concrete-filled double-skin steel tubular (CFDST) member consists of inner and outer steel tubes with concrete in-filled in the sandwiched cavity. It inherits advantages of the common concrete-filled steel tube, such as high resistance, high stiffness and good constructability. It also has some other characteristics, such as lighter self-weight and better fire performance. It is found that the inner tube can provide sufficient support to the sandwiched concrete, and the steel–concrete–steel interfaces can work together effectively under various loading conditions. The concrete-filled double-skin steel tubes may provide a better design option when designing members of large cross-sectional profiles.

1.2 Hybrid Double Skin Tubular Beams

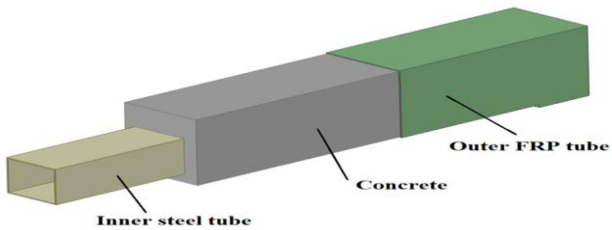
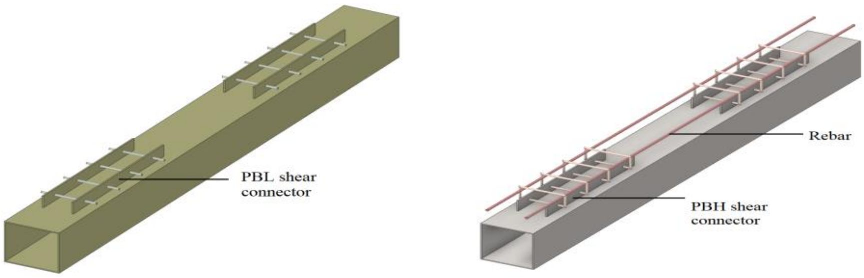


Fig 1. Hybrid double skin tubular beam

A unique composite structural member called the hybrid fiber-reinforced polymer (FRP)-concrete-steel double-skin tubular member (DSTM) was proposed by Teng et al. at The Hong Kong Polytechnic University. A hybrid DSTM typically consists of two tubes: an inner steel tube and an outer FRP tube, with concrete poured between them. Due to its ability to alter the outer and inner tube shapes to suit specific needs, hybrid DSTMs are members that are easy to design. Furthermore, hybrid DSTMs have a wider range of applications since they may be formed into beams or columns and their mechanical performance can be varied by changing the eccentricity of the inner and outer tubes. Because hybrid DSTMs can be prefabricated in factories or built on site, they are also members that are economical to construct. Hybrid DSTMs also have a number of other privileges such as (1) a supreme ductility, as the concrete is confined by both the FRP tube and the steel tube; (2) an excellent corrosion resistance due to the protection by the outer corrosion-resist FRP tube; (3) a light dead weight due to the presence of the void inside the member. In addition, compared with the traditional steel–concrete-steel double-skin member, the hybrid DSTM has a more ductile response as the outer FRP tube does not buckle. Furthermore, the corrosion resistance provided by the outer FRP tube would cut the maintenance costs. Whereas, compared with another traditional double-skin member with both inner and outer tubes made from FRP (i. e., FRP-concrete-FRP). However, there are only a few studies delved into the flexural behaviors of hybrid DSTMs as beams, i.e., hybrid double-skin tubular beams (DSTBs).The excellent ductility of hybrid DSTBs were confirmed by tests.

1.3 Role of Shear Connectors in HDSTBs

A composite beam is one whose strength depends upon the mechanical interaction between two or more materials. Slip has always existed in composite beams and will reduce the stiffness of composite beams. In HDSTBs shear connectors are used to avoid the Slip problem between concrete and inner steel tube and transfer the longitudinal shear from concrete to steel and prevent the uplifting of concrete. Perfobond hoop shear connector, abbreviated as PBH, was proposed based on the researches of PBL shear connectors. Compared to PBL, the hoops and the longitudinal bars of PBH are formed a cage. Therefore, PBH will improve the binding behavior between the concrete plate and the steel box. The deformation of the perforated steel in PBH will be constrained by both the hoop and the concrete dowel. Therefore, its overall mechanical properties will be superior to those of PBL [5]. The amount of slip of PBH is much lower than PBL when the load value is greater than 300kN. The bearing load of PBH is about 25% higher than that of PBL with 1 mm slip. However, the bearing capacity, load-displacement relationship and load-slip relationship of PBH have not been investigated deeply so far. Systematical studies, especially experimental investigations of crucial parameters on the bearing capacity, load-displacement relationship and load-slip relationship of PBH need to be carried out [5].



(a) *(b)*

Fig 2. Inner steel tube of HDSTBs having Shear connectors; (a) PBH shear connector (b) PBL shear connector

II.EXPIREMENTAL PROGRAM

2.1 Test Specimen Details

A total of four hybrid DSTBs with a length of 1500 mm were fabricated and tested in this study. All specimens were externally confined with GFRP wrapping at both direction using epoxy resin as binding agent. Each corner was rounded with a 15 mm radius arc. Due to different shapes of inner steel tubes, the four specimens were divided into two groups (with 2 specimens in each): one with a circular steel tube (140 mm in outer diameter), the other one with a square steel tube (140 × 140 mm in cross-section with 15 mm corner radius). Both circular and square steel tubes had a thickness of 4 mm. To make room for the shear connectors and also for improvement of flexural response the inner steel tubes were shifted towards the tension side of the beam by 25 mm from the center of the beam section.

Another key focus of this study is the arrangement of PBLs as shear connectors, which were welded to the top surfaces of inner steel tubes. Arrangements with two types of shear connectors PBL and PBH under investigation for each specimen group. PBL was a single piece rectangular plate (400 mm in length, 4 mm thickness and 40 mm in height) with a circular hole (8mmϕ) in the middle, with four circular holes spaced at 100 mm, and the same size of through steel deformed bars (6 mm in diameter and 140 mm length). For PBH shear connectors a single piece rectangular plate (400 mm in length, 4 mm thickness and 40 mm in height) with a circular hole (8mmϕ) in the middle, with four circular holes spaced at 100 mm and the hoop sizes (6 mm in diameter, 40 mm height and 140 mm length).

Table 1. Specimen Details

Specimen	Description	Grade of concrete	Inner Tube (mm)	PBL (mm)	PBH (mm)
PBLS	PBL with Square Tube	M 20	140 x 140	4 x 40 x 400	-
PBHS	PBH with Square Tube	M 20	140 x 140	-	4 x 40 x 400
PBLC	PBL with Circular Tube	M 20	140 mm ϕ	4 x 40 x 400	-
PBHC	PBH with Circular Tube	M 20	140 mm ϕ	-	4 x 40 x 400

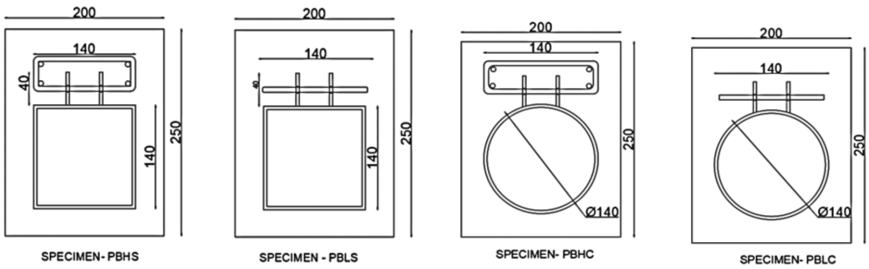


Fig 3. Cross-Sectional drawings of specimen

Table 2 Material Properties

Specimen	Density (Kg/m^3)	Elastic Modulus (GPa)	Poissons Ratio	Yeild Strength (MPa)
Steel tube	7850	200	0.3	240
Steel plate	7850	200	0.3	240
Rebar	7850	205	0.29	500
GFRP	2000	10.4	0.275	25
Concrete	2400	22.36	0.2	2.7

2.2 Specimen Preparations

Specimen preparation having following steps

1.**Steel Works**: The PBL and PBH plates were welded to the inner steel tubes, and the PBL bars and PBH hoops were positioned.

2.**Formwork Placement:** The steel tubes were placed inside the formwork, ensuring sufficient cover and incorporating additional mesh to enhance bonding.

3.Concrete Casting: M20 grade concrete was cast between the outer formwork and the inner steel tube for each hybrid DSTB.

4.Curing: The specimens were cured at room temperature for 28 days.

5.GFRP Sheets Application: GFRP sheets were then wrapped around the concrete in both directions using epoxy resin as the binding agent.

Fig 4. Steel Work Preparations

Fig 5. Specimens after Concreting

Fig 6. Cross sectional view of Square and Circular Specimens

Fig 7. Steel-FRP- Concrete Hybrid Double Skin Tubular Specimens for Testing

2.3 Instrumentation and Test Setup

The hybrid DSTB specimens were simply supported and tested under three-point bending test, with the loading applied at the mid-span of the specimen. Testing machine is loading frame and load applied manually by using hydraulic jack. Load is provided in the clear span was 1200 mm for each specimen with 150 mm clearances at both ends. Linear variable displacement transformers (LVDTs) were installed to measure the displacements of the specimen at the mid-span directly below the loading point. A data logger and an electronic digital indicator is used to measure displacement and load respectively.

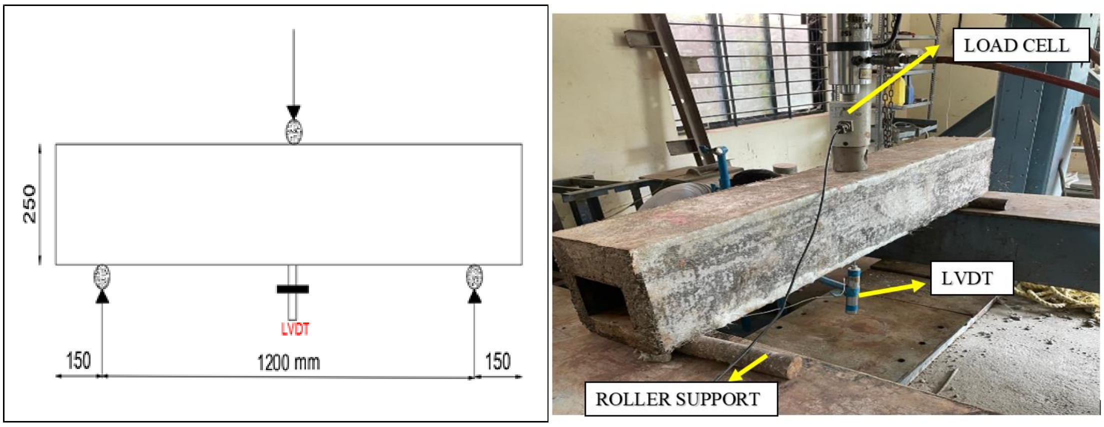


Fig 8. Experimental Test Set Up

III. EXPIREMENTAL RESULTS AND DISCUSSION

3.1 Observations and Failure Modes

Generally, the failure modes of all specimens had a similar pattern that a huge through crack has formed either directly below or next to the loading point. The major tensile cracks appeared when the applied load reached around 150 kN and 200 kN for Circular and Square specimens, respectively. With the tests continued, the major tensile cracks grew wider on the tension side and propagated gradually to the compression side of the beam. When the mid-span deflection arrived at around 15 mm, concrete bulging was clearly visible next to the loading head, but only occurred at one side of the loading head. The transverse bars of PBL shear connectors are act as crack propagating points in concrete. But in PBH connectors there is no transverse rebar, instead of that there is hoops with no pointed surface. Therefore the specimens having PBH connectors have less chance to propagate cracks inside the specimens.

Ultimately, GFRP tube rupture occurred at the mid-span of the beam when the mid-span deflections were around 20 mm. Generally, no severe damages and no sight of GFRP tube rupture were observed for all specimens. A number of tensile cracks were noted on the tension side of the GFRP tubes, manifesting as white patches on tubes. Significant concrete crushing can be viewed after removing the GFRP tubes. However, the integrity of PBL and PBH connectors did not compromise, only minor damages and very small deformations were noticed on some through bars, which demonstrated the effectiveness of the PBL and PBH connectors.

3.2 Load – Deflection Behaviour of HDSTBS

The typical mid-span load–deflection curve of a structural element, such as a hybrid double-skin tubular beam, can be divided into three main branches, each representing different stages of the beam's response to loading:

1. Linear Ascending Branch: In this initial stage, the beam's deflection increases linearly. The relationship between the load and deflection is linear, indicating that the material behaves elastically. During this phase, the beam is within its elastic limit, meaning that it will return to its original shape if the load is removed. The stiffness of the beam is constant in this region, and no permanent deformation occurs.

2. Transition Branch: This stage occurs when the curve starts to deviate from linearity, indicating the onset of non-linear behavior. In this transition phase, the material begins to yield and plastic deformation starts to occur. The stiffness of the beam decreases as it approaches its ultimate load capacity. Micro-cracking, yielding of materials, or other forms of non-linear behavior may begin in this region. The beam is transitioning from elastic behavior to a plastic state, where permanent deformations start to develop.

3. Post-Peak Descending Branch: After reaching the peak load the load begins to decrease even as deflection continues to increase. This stage represents the post-peak behavior of the beam. The beam has surpassed its maximum load-bearing capacity, and damage is accumulating. Significant plastic deformation occurs, and the stiffness of the beam further decreases. This descending branch indicates the failure or significant degradation of the beam's structural integrity. The beam's material might be experiencing crushing, extensive cracking, or other forms of damage that lead to a reduction in load-carrying capacity.

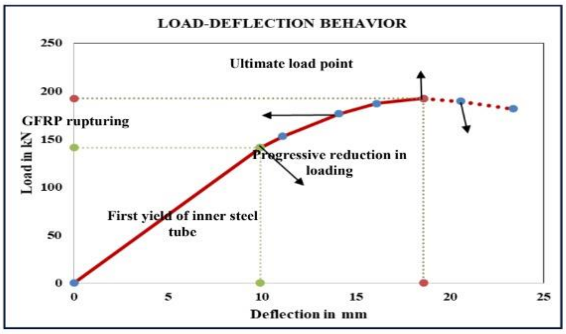


Fig 10 Typical load–deflection behavior of hybrid DSTBs under three-point bending

Fig 9. Different Failure modes of HDSTBs

3.3 Ductility and Stiffness

Ductility refers to the ability of a material to undergo significant plastic deformation before failure. Ductile beams can absorb and dissipate a substantial amount of energy through plastic deformation. This is particularly beneficial in applications where dynamic or impact loads are expected, such as in seismic regions. Stiffness contributes to the overall stability of a structure. In beams, it helps in maintaining the desired shape and alignment under various loading conditions, ensuring the structural system behaves as intended.

Table 3. Stiffness and Ductility of HDSTBs

Specimen	Load Values In kN		Deflection In mm		Ductility	Stiffness (kN/mm)
	Ultimate	Yield	Ultimate	Yield		
PBLS	181.1	168.8	9.2	6.1	1.508	19.68
PBHS	192.2	141	18.6	9.9	1.878	10.33

PBLC	157	126	13.9	8.1	1.679	11.29
PBHC	161.9	120.9	12.5	7.1	1.760	12.95

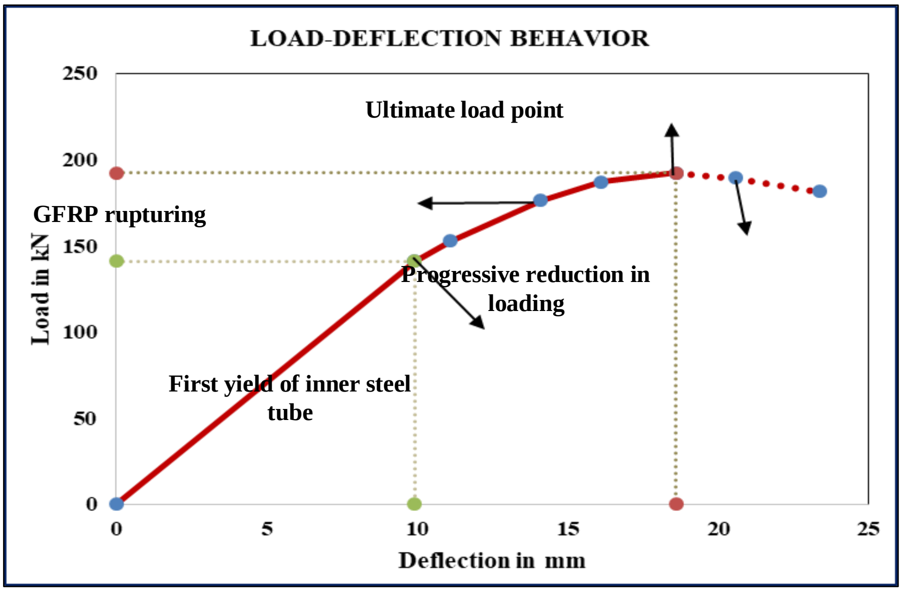


Fig 10 Typical load–deflection behavior of hybrid DSTBs under three-point bending

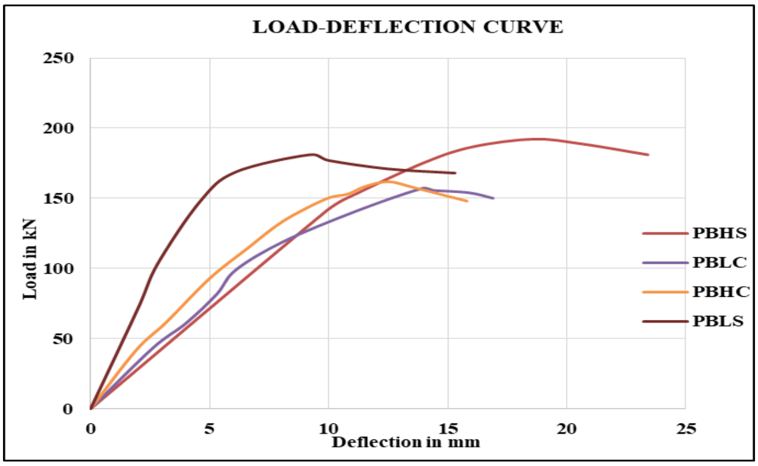
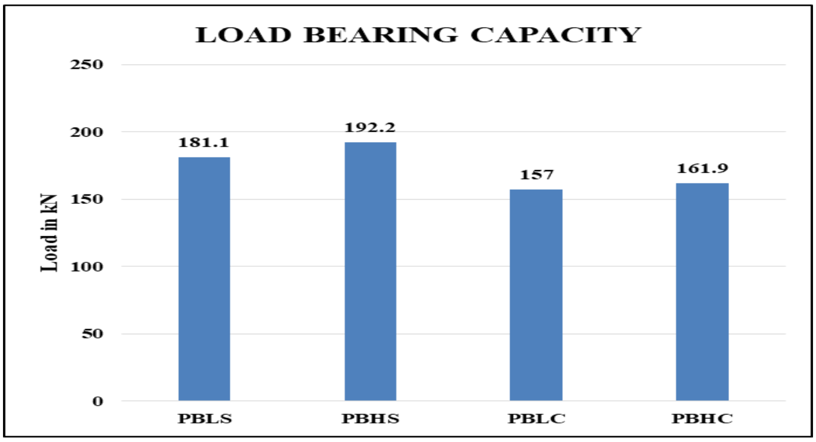
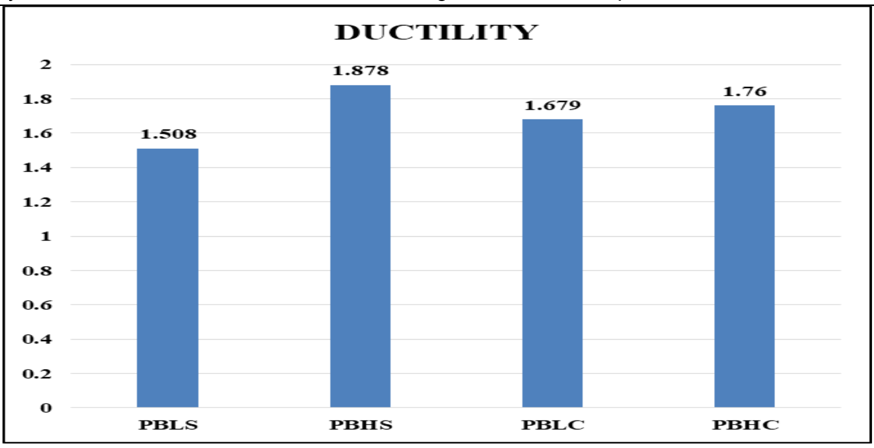


Fig 11. Load Deflection Behavior of All Specimen



(a)



(b)

Fig 11 Comparison charts: (a) Load bearing capacity, (b) Ductility,

IV. CONCLUSION

Four type hybrid DSTB specimens with different inner steel tube shapes and different shear connectors are were tested under three-point bending. The results of failure modes, load–deflection behavior, ductility, Stiffness are obtained. The main findings are summarized below:

1. The specimens typically failed from the gradual propagation of a major tensile crack in the mid-span. Concrete bulging associated GFRP tube rupture in the compression side was visible. However, the concrete sections to which shear connectors are attached have experienced minimal or no damage, and the shear connectors both PBH and PBL themselves remain intact
2. The findings from comprehensive experimental and analytical investigations indicate a increase in strength between the PBH shear connector and the PBL shear connector. On average, the PBH shear connector demonstrates a higher strength of approximately 4.4% when compared to the PBL shear connector. This increase in strength is due to the presence of hoops and longitudinal bars in the PBH shear connector, which transfer shear forces more effectively than the transverse bars in PBL
3. The use of PBH shear connectors in HDSTB specimens enhances their ductile behavior. This is because crack propagation within PBH specimens occurs gradually, exhibiting crack resistance. In contrast, PBL shear connectors, which have pointed edges due to the transverse bars, tend to cause and propagate cracks quickly. PBH shear connectors, on the other hand, feature hoops instead of pointed edges. These hoops do not initiate cracks, contributing to the increased crack resistance of HDSTB specimens with PBH shear connectors
4. It was also observed that specimens with a square inner tube demonstrated superior load-bearing capacity, averaging 14.53% higher compared to those with a circular inner tube. This improvement is attributed to the larger contact area provided by the square tube compared to the circular tube.
5. There has been no slip observed between the top portion of the inner steel tube and the surrounding concrete
6. The outer GFRP skin plays a vital role in HDSTBs by providing effective confinement, improving bonding performance, increasing load-bearing capacity, and ductility. The GFRP skin experienced rupture due to the bulging of the inner concrete, which took place when the specimen was nearing its ultimate load capacity.

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