ADVANCED COMPOSITE MATERIALS IN BRIDGES AND STRUCTURES
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EXPERIMENTAL STUDY ON OUTSIDE FILAMENT WINDING REINFORCED FRP BRIDGE DECKS

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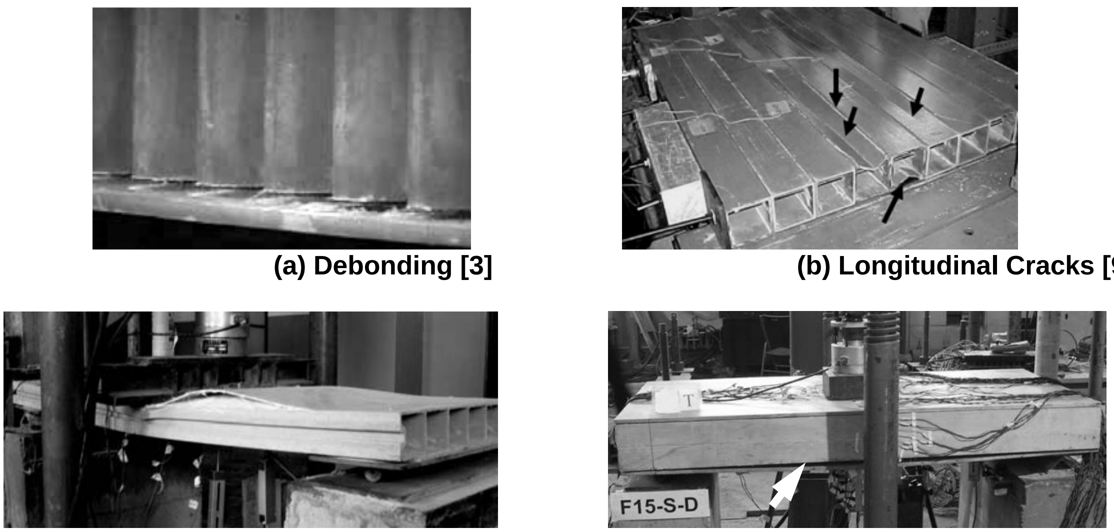
ABSTRACT: Innovated FRP (Fiber Reinforced Polymer) bridge deck system is gradually applied widely in the recent years. Many FRP deck products by varied processes were created and manufactured. In the decks, local delamitation, debonding and buckling are usually the ultimate failure modes that cause the FRP strength not to be utilized fully and result in a sudden or brittle failure. In this paper, a concept of improving the mechanical performance of FRP decks by outside filament winding is presented. Two sets of experiments are conducted in order to compare the suggested filament wound FRP decks with the others without winding under static load. In the tests, the ultimate load of the pultruded shaped plank increased largely and the stiffness improved obviously by the filament winding. The ultimate deformation capacity of the combined deck was enhanced greatly. Pseudo ductility appeared in the filament wound combined deck. Based on the experimental results, the mechanism of the outside filament winding which provides not only the additional shear and torsion stiffness but also the confinement is analyzed. The finite element analysis also proves that the outside filament winding can effectively improve the performance of FRP bridge decks.

1. INTRODUCTION

The deterioration of the steel reinforced concrete and steel bridge decks is becoming a worldwide disease. It is not only a structure problem, but also is a poison to the traffic safety. In the Unite States, a significant number of bridges with a superstructure of age below 50 years which is almost half of the expected service life were classified in poor condition because of deck deterioration by 1995. The total estimated cost of bringing up the deficient bridge superstructures to an acceptable level is $110 billion [1]. Corrosion of the steel reinforcement and steel members is a primary cause for the deterioration. In northern China, the deterioration due to the corrosion by deicing salt in many bridges built in the recent 25 years is becoming a severe problem. The investigation in 1997 concluded that the steel corrosion by deicing salt is the uppermost reason for debasing the durability of bridges in Beijing [2]. In the recent decade, FRP decks, which have the favorable properties like corrosion resistance, low weight, good fatigue performance, rapid construction, and low maintenance cost, are increasingly used in bridges to replace the deteriorated decks or act as elements in new bridges. Many kinds of FRP decks were studied and applied in some bridges [3-14]. The composite manufacturing processes, including layup, VARTM (Vacuum Aided Resin Transfer Molding), pultrusion and filament winding, are employed to make the modular products and even several processes are used for one product. Table 1 shows classification of some FRP decks being studied and applied according to the configurations.

Table 1 – Classification of FRP decks.

Configuration	Fabrication/assembly		Representative literatures/cases
Sandwich decks	Hand/automated Layup		[3], [14] No-name Creek Bridge(USA)
	RTM/VARTM		[4] Bentley's Bridge(USA)
Modular pultruded profile decks	Coupled		[5], Rama VIII Bridge Enclosure System(Thailand)
	Bolted		[6],[7]
	Bonded		[6],[7],[8] Wickwire Run Bridge(USA)
	Prestressed		[9]
	Combined Above		[7]
Decks combined with profiles and face plates	Tubes	Pultruded	[10],[11]
		Filament wound	[12]
	Face Plates	Pultruded	[11]
		Layup	[10],[12]
Other all-FRP bridge superstructures	Layup box beams		[2] Miyun Bridge(China)
	Pultruded beams		Bond Mill Bridge(UK)
	Assembled pultruded tubes		[13]



(a) Debonding [3] **(b) Longitudinal Cracks [9]**

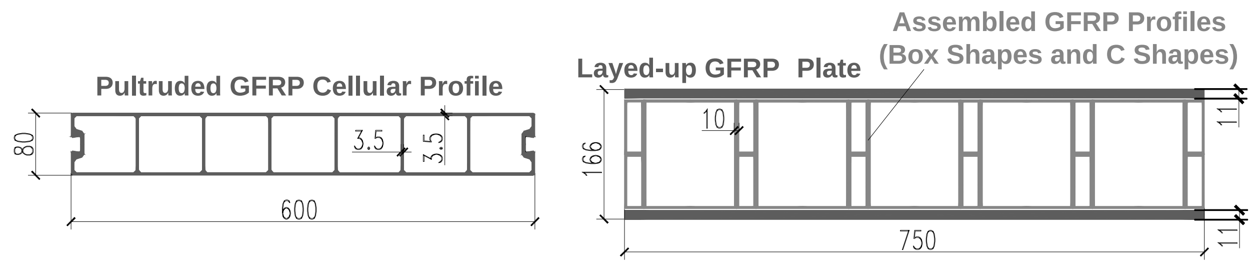
(c) Delamination : SP **(d) Debonding : FD**

Fig. 1 – Failure Modes of FRP Decks.

Most of the research work in predicting bending deflections of FRP decks is available in literatures. The ultimate behavior is important to determine safety factor of FRP decks. The failure modes of FRP decks can be classified as: (1) the FRP strength failure, including material strengths in longitude, transverse and interlaminar; (2) the assembly failure, including debonding, pullout, and collapse; (3) the local buckling, including in the flange, web and honeycomb wall. Different failure modes correlate with different behaviors. The debonding between the core and the skin of the sandwich FRP decks is shown in Fig.1(a) [3]. Examples of longitudinal cracking failure and delamination failure in the modular pultruded profile decks are shown in Fig.1(b) [9] and Fig.1(c) separately, because the majority of fibers are along the longitudinal direction so that the transverse and interlaminar shear strength are lower. For the decks assembled with profiles and face plates bonded by resin, the bonding interface is weak. Thus, the failure mode of the debonding shown in Fig.1(d) is unavoidable. In the failure modes shown in Fig.1, the FRP's longitudinal strength cannot be utilized sufficiently. The damage always starts at the worst property, which leads to the failure of whole deck. Therefore, it is reasonable to believe that the performance of the decks can be improved by preventing these failure modes. In the paper, outside filament winding is suggested. Two different kinds of FRP decks, one with 80mm thick pultruded shaped plank and the other with 166mm thick combined cellular deck, are wrapped by glass fiber filament winding of 2.2mm thickness and ±80°crossing orientation. The decks with and without winding are tested and studied to compare their performance.

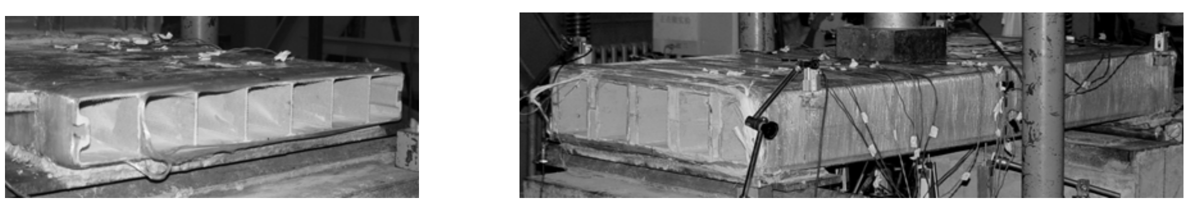
2. EXPERIMENTAL PROGRAM

The main objective of the testing program is to compare the behaviors of the decks with and without outside filament winding under the static load. Two different configurations of FRP decks are tested. The specimen named SP is GFRP modular pultruded profile as shown in Fig.2(a), and the other named FD is combined FRP deck using GFRP profiles and face plates, as shown in Fig.2(b). The SP deck is formed with E-glass rovings (4800 Tex), continuous strand mat and unsaturated polyester resin. The profiles in the FD deck are bonded and bolted as the core, which is bonded with the face plates. The pultrusions are composed of E-glass rovings (2400 Tex), continuous strand mat and unsaturated polyester resin, the plates are laid up with E-glass strand mat and unsaturated polyester resin, and epoxy resin bonds them together. Their coupon properties are tested and provided by the manufacturers, as listed in the Table 2.



(a) SP **(b) FD**

Fig. 2 – Configurations of Specimens without Reinforcement.



(a) SPW **(b) FDW**

Fig. 3 – Photos of Specimens with Reinforcement

Table 2 – Coupon properties of specimens (provide by manufacturers).

Deck		Properties	Value *	Properties	Value *
SP		Tensile strength (MPa)	210/72	Tensile module (GPa)	22/10
		Compressive strength (MPa)	258/98	Compressive module (GPa)	19.2/7.2
		In-plane shear strength (MPa)	24.5	Poisson ratio	0.29
FD	Profiles	Tensile strength (MPa)	310/90	Tensile module (GPa)	24/8.5
		Shear module (GPa)	4.2	Poisson ratio	0.27
	Plates	Tensile strength (MPa)	228/257	Tensile module (GPa)	14.3/17.6
		Shear module (GPa)	3.5	Poisson ratio	0.15
	Adhesive	Tensile strength (MPa)	44	Yang's module (GPa)	3.2
		Shear strength (MPa)	23	Poisson ratio	0.35

*: Two values in one cell are in two directions: lengthwise / crosswise.

To improve the performance of the decks, the filament layer is wound around the deck's cross section. The E-glass rovings (1200 Tex) and epoxy resin compose the filament wound layer of 2.2mm thick. The winding angle is ±80^{o} and the fiber volume fraction is 0.55. SP and FD with outside filament wound layer are called SPW and FDW respectively, as shown in Fig.3. Altogether, there are four specimens in the test program: SP, SPW, FD and FDW.

The length of all specimens is 1500mm with the simply supported span of 1300mm. For the SP and SPW, the load was applied at the center of the span distributed over the deck's width with a 100 mm wide steel beam, which is displayed in Fig.1 (c). For the FD and FDW, the load was applied at the center of the deck over a 200x200 mm steel plate to simulate the wheel load at local, which is displayed in Fig.1 (d). There were 106 strain gauges pasted on the surface of each specimen. Displacement transducers were located at the supports and inner span.

3. EXPERIMENTAL RESULTS

3.1 SP vs. SPW

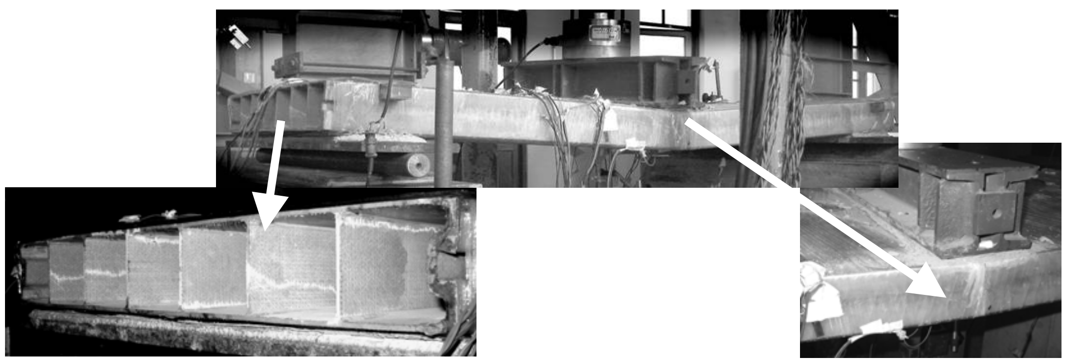
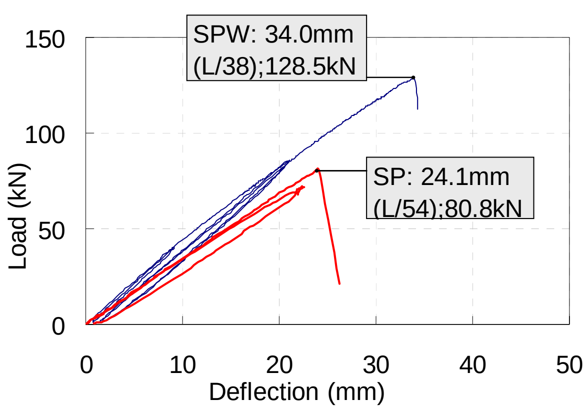


Fig. 4 – Cracking in SPW.



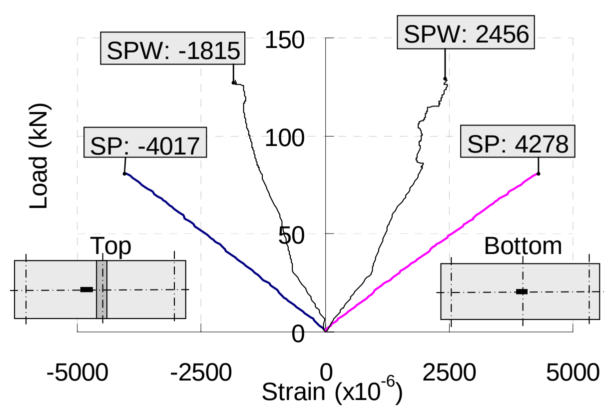


Fig. 5 – Load-deflection Curves for SP and SPW. **Fig. 6 – Load-strain Curves for SP and SPW.**

The load was applied gradually to avoid sudden collapse. Some clacks began to appear for SP when the load reached 30kN, while it was at 40kN for SPW. However, it was noticed that there was no sound emitted when the load reached the same level in the second loading after unloading from the evaluated maximum load. It can be concluded that the clacks are signal of the damage developing. With continuous increasing in load, denser clacks were heard. The SP reached its ultimate load by sounding loudly during failure, a crack along the top edge of the section occurred on one side and the top plate delaminated and buckled. The thickness of delaminated layer was about 3mm and the crack length was about 480 mm. The failure mode is shown in Fig.1(c). Moreover, there was a crack on the other edge of the decks. For SPW, it had shown a similar behavior as load increasing except that the ultimate load was much higher than SP and resulted in a different failure mode. At the ultimate failure point, longitudinal crack appeared on each inner web (Fig.4). The cracks extended from the center of the span to one support end only in one half of the span. However under the distributing beam at the center loading place there was a vertical crack on the outside wound layer (Fig.4). Both SP and SPW almost displayed linear behavior throughout the loading history, as shown in Fig.5. Furthermore the longitudinal strain versus load also showed linear relationship as shown in Fig.6. Compared with SP, the ultimate load of SPW increased 59% and 12.7% for the stiffness.

3.2 FD vs. FDW

Because of the local load are applied at the center of decks, FD and FDW are bended in two directions with two simply supported sides and the other two free sides. As load increased, the phenomena of the clacks observed were same as that in SP and SPW, but here it was more evident. For FD, the first clack load was 50kN and the behavior was linear until the ultimate load 256kN. However, the behavior of FDW was much different as the pseudo ductility appeared. The load-deflection curves are shown in Fig.7. In the curve of FDW, the point at 276kN load and 12.8mm deflection can be defined as the yield point, while the failure deflection is 29.1mm and the maximum load is 299kN. The longitudinal strains are shown in Fig.8. The FD's curve and the initial part of FDW's curve are nearly linear elastic under loading and unloading. The FDW's strain in pseudo ductility phase did not run up smoothly with the sustained grown deflection but jumped up and down with the load. So the ductile behavior was not provided by the plastic deformation of the material, as FRP is known as a linear elastic material, but actually by the fraction and sliding of the interface between the components. The ultimate deflection of FDW is recoverable with unloading as shown in Fig.7. FD failure mode was the debonding between the assembled profiles and the bottom plate as shown in Fig.1(d). For FDW, the failure mode was changed, as shown in Fig.9, due to the outside filament winding which confined the assembled profiles and the plates. The ultimate failure caused by the cracks in the two webs under the loading patch. The load patch was sunken obviously. And there was a slippage between the profiles and the bottom plate. Compared with FD, the maximum load of FDW increased 16.8% although with a little increase in stiffness, and it is the most significant that the deformability of FDW was more than doubled and has a yieldable characteristic.

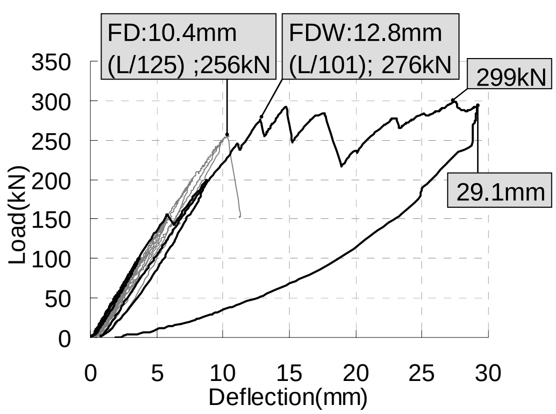


Fig. 7 – **Load-strain Curves for FD and FDW.**

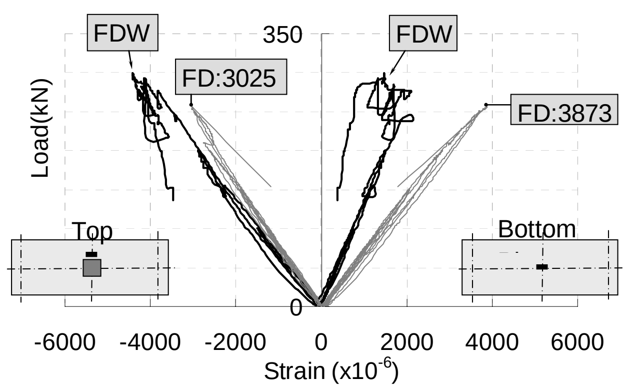


Fig. 8 – **Load-strain Curves for FD and FDW.**

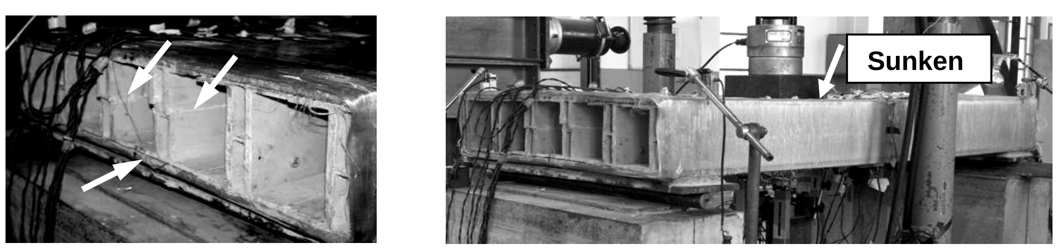


Fig. 9 – **Failure Mode of FDW.**

4. ANALYSIS

4.1 Deflection Prediction

Many analytical models to predict the load-deflection behaviour of FRP decks were presented and developed in last two decades. The properties of profiles are determined with Classical Laminate Theory (CLT) [7] or testing, and the deflections can be predicted based on the assumptions of perfect bonding or assembly and linear elastic behaviour using the systematic method presented by Davalos [15], Qiao [16] and Williams [12]. The outside filament winding are modelled as the outermost layer of the decks. The actual decks were simulated with FEA (finite element analysis) and the deflections were predicted also. The results of the centre deflections are listed in Table 3. Though the results of the systematic method and the FEA corresponded well with the test results with a percent error below 15%, however the stiffness of the assembled or the wrapped decks, SPW, FD and FDW is over-estimated universally which suggests that the bonding and the assembly are not as perfect as the assumption. Anyway, the outside filament wound decks stiffness can be predicted in an acceptable range using systematic method and FEA.

Table 3 – **Compare defections by three methods**

Specimens/load(kN)	**Test (mm)**	**Systematic method (mm)**	**FEA (mm)**
SP / 80.8	24.13	25.25 (+ 4.6%)	25.62 (+ 6.2%)
SPW / 128.5	34.02	31.61 (- 7.1%)	32.94 (-3.2%)
FD / 256.0	10.40	9.49 (-8.8%)	9.11 (-12.4%)
FDW / 276.0	12.83	11.25 (-12.3%)	11.01 (-14.2%)

4.2 Failure Modes

For SP, without outside wrapping, there are the potential failure modes: buckling of the top plate, buckling of the webs, delamination in plate for shearing, collapsing in plate or web for compression, cracking in webs for shearing, rupturing in tension. In the test, the delamination from the edge of top plate occurred firstly. The shear stress in top plate is calculated with FEA, as shown in Fig.10. The white parts mean the stress over the strength in the maximum stress criteria under the ultimate load.

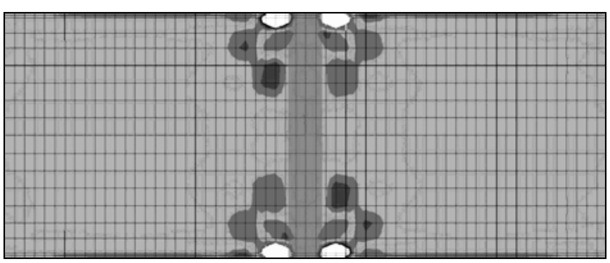


Fig. 10 – **Shear Stress in Top Plate of SP.**

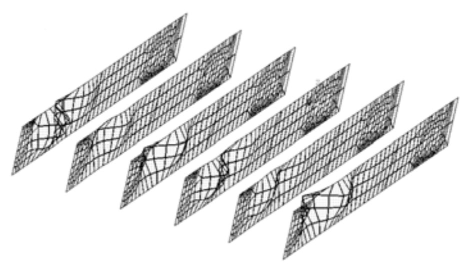
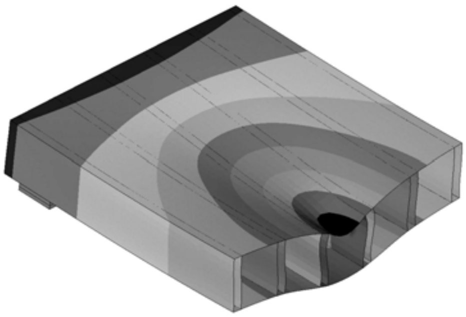


Fig. 11 – **Buckling of Inner Webs of SPW.**

In SPW, the outside wound filaments increase the shear strength and restrict the trend of delamination in these parts, whereas the inner webs become weaker relatively, so the failure occurred from here. The buckling failure of the webs is believed and the shear failure is excluded because all the cracking came out at the same instant. The first order character bulking mode of SPW is the six inner webs' buckling as shown in Fig.11, which is a half model with symmetry. The character load is 1.02 times ultimate load in test which is higher than the ultimate load of SP. Therefore, it is concluded that the behaviour of the deck were improved with the failure modes shift.

The deformation mode simulated by FEA for FD is shown in Fig.12. The debonding occurred between the bottom plate and the core firstly due to the failure of the adhesive resin. In FDW with the outside filament winding layer, the adhesive resin failed at same load level also. However, the shear stress is still able to be transferred in the interface for the outside layer constriction. Increasing of the deflection after the pseudo yield point, the stress in the assembled profiles accreted while the composite action weakened. At the ultimate point, the failure of the whole deck is caused by the shear cracking of the profiles in core. The relations are illustrated in Fig.13. The combined deck with outside reinforcement has a two-phase failure mode. The end of the first phase is debonding, the second phase extended by the wound filaments until the shear failure of the profiles occurred which would have failed also if the profiles had been loaded in same deflection separately.



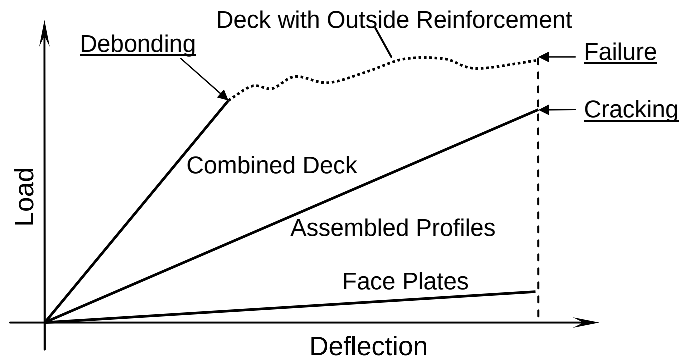


Fig. 12 –Deformation Mode of FD **Fig. 13 –Load-deflection Relations of FRP components**

From the experimental results and the above analysis, it is concluded that the failure mode controlled the ultimate behaviour. Therefore, controlling of the failure behaviour should be considered in FRP deck design.

4.3 Enhancement of Outside Filament Winding

The outside filament winding layer configuration improved the behaviour obviously. It acts as three roles for the deck. The first is the transverse stiffness of the face plate can be increased due to the substantive transverse fiber in it. The second is the torsion stiffness of the section can be increased too. The wound filament layer in the section is a rectangular box actually which can provide torsion stiffness. These two can be considered in the systematic method. The third one is that the outside filaments confine the deck and resist the trend of swelling and dispreading. The buckling and the assembly are confined and the friction between the profiles is provided. However, this role cannot be considered in linear elastic method. This problem should be studied in future work.

5. CONCLUSIONS

An experimental program studying the behaviors of FRP decks was undertaken. The outside filament winding for reinforcing the decks is presented and proved. Two different configurations of decks are tested and analyzed. The conclusions are summarized as below:

- The outside filament winding reinforcement is an effective approach to improve the performance of FRP decks, which were proved in the tests by the accretion of the ultimate load of SPW and the ultimate deflection of FDW.
- Pseudo ductility can be provided by outside reinforcement in the combined deck that can increase the deformation capacity of FRP decks and alters the failure mode.
- Deformation of outside filament wound decks can be predicted with systematic method and FEA, though a little over-estimation in stiffness cannot be avoided.
- The failure modes of FRP deck decide the ultimate behavior that should be considered in FRP deck design.
- The mechanism of the outside filament winding enhancement is that the filaments increase the transverse stiffness of the face plate and the torsion stiffness of the section and resist the swelling and dispreading trend of the components.

Furthermore investigations should be carried out to present the more detail approach to control the failure mode and to determine the ductility factor accurately.

6. ACKNOWLEDGEMENT

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