Review on pultruded FRP structural design for building construction

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Abstract. Fibre reinforced polymer (FRP) have been used in civil engineering for past few years. Researches often argue that available design standard practice are lack of practical design details to be used in structure design. This paper reviews the recent researches of pultruded FRP structural design in civil engineering focusing these fours aspects of area. The design consideration in these areas are relatively important for structural designer to focus. These consist of environments impact, dynamics responses, issue of connection, and buckling design. For environment impact, review focus on the severity of artificial ageing and natural ageing to material mechanical properties, as pultruded FRP structures are now used by industries which require serviceability for harsh environment. Due to the low weight stiffness ratio of FRPs structure, vibration effect is in large degree of extent. Unlike steel structures, pultruded FRP structures are using only the bolting connection. Hence, it is crucial to understand the bolting in detail. For buckling issue, studies of interaction of local and global buckling is often suggested by researches.

1. Introduction
Fibre reinforced polymer (FRP) have been used in civil engineering application in the past few years due to its several attractive performances. On a common ground of civil engineering researchers, FRP have been labelled as material with high strength-to-weight ratio, high stiffness-to-weight-ratios, ease of installation, high corrosion resistance, high durability, and high tailorable for construction. In the last decade, FRP application have been widely used in pedestrian bridges, building, pipelines, offshore energy sector and some other basic infrastructures [1]–[15]. In the past decade, both experiments and numerical studies on many aspects of pultruded FRP structures. There are important aspects that form the basis of structural design in civil engineering and plenty of research works need to be done as many of the aspects of application in civil structures design are unknown. Besides of static calculation design, there are many important areas that require high attention for design purposes. The important design consideration for pultruded FRP structures are environments impact, dynamics responses, issue of connection, and buckling design. For environment factors, pultruded FRP structures often used in replacing conversational steel material. Although there are material manufacturer provides certain level of precaution, there are inadequate of data validation to effect of environment impact. Severity of environmental impact on mechanical properties of pultruded FRP structures are often unknown [16]–[18]. In another hand, dynamics response is a popular topic in general civil structural engineering. Furthermore, pultruded FRP structures consist of lower weight and stiffness compare to steel structure. In terms of serviceability, pultruded FRP structures required extra design care in order to minimize the vibration effect on the structure [3],[5]. Besides that, joining system for pultruded FRP structures is an
interesting area since the bolts material is in steel while the joining parts such as web cleat, splice plate, and gussets are in FRP material. Due to lack of design standards with FRP structural joining, and reliable joining details. The connection studies became one of the essential topics for studies in pultruded FRP structures [7], [9]. Pultruded FRP structural members contain profile form by thin plates with both closed or open cross section. Detail design shall often involve local and global buckling. In recent studies, plenty of experimental investigation and numerical studies conducted to the local and global buckling [22]–[27]. This paper brief about the severity of environmental impact on mechanical properties of pultruded FRP, dynamics responses of pultruded FRP structure, bolt connection design, and load and global buckling design of pultruded FPR structure.

2. Severity of Environmental Impact on Mechanical Properties

Despite its excellent serviceability in numerous of industries, FRP have similar aging or degrading issues like other materials. This has raised questions on the effects happen to the material properties in short or long run within different harsh environment conditions. In fact, this is insufficient to only meeting the design requirement of varies standard practice in building, energy, chemical, petrochemical, oil, and water industries. To large extent, thermal cyclic loading, chemical, seawater affecting the mechanical properties of FRP [28]–[33]. Other natural effects that accelerates the ageing of FRP materials are exposure to high temperature, freeze-thaw cycles, humidity and UV radiation. There is unclear correlation between the artificial and natural ageing and require further theoretical modelling claimed by G.Carra & V. Carvelli [16].

Researchers claims that reason of slow acceptance of FRP structural application is mainly due to inadequate of data validation on environment factors such as seawater, variation of temperature, humidity, alkalinity reactions from concrete and corrosive medium. Bazli, et.al [18] investigated performance of pultruded FRP under harsh environment through experimental method. The research found that pultruded FRP structures performance consistently reduced due to alkaline solution, seawater, elevated temperature and acidic solutions. Alkaline with PH =13.6 has the most effective degradation of strength and followed by acidic degradation as second, while least reduction caused by elevated temperature. Therefore, in comparison of chemical and temperature effect, alkaline attack playing the most significant role.

In view of thermal effect alone, there is no significant reduction of strength to FRP material. Similarly, residual strength of FRP material remains higher than wood and concrete found in the elevated temperate experiments conducted by Behzad, et.al. [34] to predict the mechanical properties under temperature duress. No significant loss of ductility and 75% loading capacity recover after being subjected to 200°C elevated temperature in the experiment. This further agreed by Sotirios, et.al. [15] that negligible degradation of tensile and shear strength found in dry sample testing. However, soaked sample shows significant reduction of both tensile and shear strength. Despite the degradation, material stiffness does not change in large degree of extent. This statement claimed similarly by M. Pour-Ghaz, et.al [28], 8-10% reduction of strength occur after 1000 hours and 10-20% after 2000h to pultruded FRP with high grade vinyl ester resin basis under freshwater or saltwater at elevated temperature of 60°C. Similarly, the polyester grade pultruded FRP has 5-15% reduction of strength after 1000h and 15-18% after 2000h in both freshwater and saltwater conditions.
Figure 1. Residual tensile strength of vinylester GFRP normalized to the post-cured strength after (a) 1000 h of conditioning in freshwater, (b) 1000 h of conditioning in saltwater, (c) 2000 h of conditioning in freshwater, (d) 2000 h of conditioning in saltwater (from M. Pour-Ghaz, et.al, 2016, p.351)

Figure 2. Residual tensile strength of polyester GFRP normalized to the post-cured strength after (a) 1000 h of conditioning in freshwater, (b) 1000 h of conditioning in saltwater, (c) 2000 h of conditioning in freshwater, (d) 2000 h of conditioning in saltwater (from M. Pour-Ghaz, et.al, 2016, p.352)
In comparison of all reviewed papers, research works done by researchers are well presented. Nevertheless, none of the works draws conclusion or recommendation back into the civil structure design consideration. Service design factor shall be quantified to provide designer a good reference for pultruded FRP structural design.

3. Dynamics Responses of Pultruded FRP Structures

As mentioned in introduction, light weight properties make pultruded FRP structures an excellent option for many civil structures. However, FRP structures have excessive vibration serviceability issues due to relative lower weight and stiffness compare to steel materials [3]. The fundamental of vibration consists of three main governing components, mass, damping and stiffness of the structures. Influences of human activities, damping characteristics, natural frequencies are difficult to predict [19]. Classical closed-form solutions to evaluate natural frequencies of axially loaded beam such as by Euler-Bernoulli and Timoshenko beam theories. However, flexural-torsional vibration not included in analysis. Minghini, F., et.al. [35] attempt to evaluate the frequencies of mode shapes and investigate the effect of geometrics, shear deformations, and mass on a loaded FRP structures frames by the locking free finite elements formulation. Authors further argue that geometrics and mass increase of FRP frames greatly reduces the natural frequencies. Approximately 20% overestimation of buckling and natural frequencies for neglecting the shear strain effects. Therefore, knowing the effect of geometrics and shear deformation due to flexural-torsional vibration help to reduce the overestimation of buckling and natural frequencies.

In view of critical buckling load, it is crucial to understand the effect combination of static and dynamics on FRP pultruded structure. Critical buckling load of a FRP pultruded column have been investigated by Jungtae Noh [12]. Finite element model shows that dynamic buckling loads have significant sensitivity to model’s boundary conditions. Authors suggested that full numerical studies on both static and dynamics load is needed for a safe design of FRP elements. Therefore, studies on mass and geometric effect has important role in dynamics response of structural design.

Figure 3. Dynamic buckling mode of FE sheet pile models: (a) 1m and (b) 9m (C-F). (From Jungtae Noh, 2017)

In terms of the third governing components of vibration, the rigidity stiffness has significant control on the vibration system. Structure with high rigidity due to over design from static calculation does not reflect a safe structure design in dynamics responses. Structure connection with pinned joints in FRP structure frames unable to resist vibration while rigid joints maybe difficult and costly to be designed. Minghini, et.al. [36] have demonstrated the performance of semi-rigid connection of
Pultruded FRP frames subjected vibration base on Hermitian Locking-free theory under two-node application. The result shows the reduction of frequency up to 70% to 80% which approximately the mean of pinned joints and rigid connection. Stiffness consideration is significant in structure dynamics design. Another example claimed by Russell, et.al. [3], that the vibration response of the pultruded FRP footbridge is negligible with well design of lateral stiffness. The author uses hammer impact test to identify the modal properties of bridge to determine the dynamic response.

The most critical reason of dynamics study on civil structures is to determine seismic effect on building. Dynamics response is a major design consideration where seismic requirement exist. Lighter properties of pultruded FRP material has lower density and therefore lead to less advantages against seismic load. For pultruded FRP material to be applicable, knowledge about the dynamics parameters shall be broadly understood. One of the good comparative study from Boscato, G. [8], has investigate the dynamic parameter of pultruded FRP material acting as structural members through determining the mode shapes of members and resonance conditions simulated with the damping ratio. The author classifies dynamic properties of FRP into high phase vibration, base frequencies and dissipative capacity against seismic activities, see figure 4. Boundary conditions is crucial factor to govern dynamic behaviour. It makes varies flexural rigidity that determine damping ratio and structure dissipative capacity. Damping ratio is smaller in a fixed end setting while higher in simply supported setting.

In comparison of all reviewed papers, research works done by researchers are well presented with numerical studies. There are less recent studies using experimental setup and less practical closed-form equation developed represents vibration behaviour in pultruded FRP structures. The closed-form equation which relates to various parameters could ease for design practitioner to perform design calculation in dynamics.

4. Bolted Connections Design
Large numbers of early studies on FRP composite structure joining is available on aerospace industry. Structural joining for civil engineering has essential gap between the design used by aerospace, that is, civil engineering requires frame connection between structure members while aerospace joining require shell structures joining methodology. In the current joining methodology in civil structures, pultruded FRP members use steel bolting with pultruded FRP splice plating or web cleats as tying members. [6], [7]. However, due to lack of design standards with FRP structural joining, and reliable joining details. The connection studies became one of the essential topics for studies in pultruded FRP structures.

Classic approach to joint connection limited to nominal pinned or rigid. Recent studies by Qureshi, et.al [9] argued that moment-rotation exist in all type of joints required extensive understanding. Authors conducted experiments on pultruded FRP beam-to-column frame with FRP web cleats to find out the characteristics of moment-rotation response of pinned joints, see figure 5. The experiments show that structure failure does not depends on numbers of bolting, however, moment rotation significantly affecting structure. Suggestion given for design standard of limit state deflection to L/250 in normal operating environment and L/340 for aggressive environment.
**Figure 4.** Formation of dissipative points for different frames (From Boscato, G., 2017)

**Figure 5.** Experiment setup for beam-to-column joints - 1 (From Qureshi, et.al, 2015)
More detail studies in 2017, researcher like Matharu, et.al. [11] conducted experimental test on effect of pin-bearing strength with plain bolt and threaded bolt. In additions, the fibre reinforce orientation angle Authors argue that reduction factor of 0.6 introduced by America LRFD pre-standard in 2010 only for threaded bolt design and continuous mat only. Result from experiment suggests that reduction factor is acceptable and confirm that the thread has significant contribution on pin-bearing strength and shall not be ignored in design. The result is well present the behaviour of threaded bolt. However, no numerical studies to investigate and verify further for the pin-bearing strength.

There are quite several numerical studies on bolted connections for pultruded FRP structures. Researchers like Feo, L. et.al. [6] conducted numerical studies with finite element analysis approach on tensile loadings on varies bolting joints. The result shows that bolting position, bolt hole clearance, tightening torque, material interface friction are factors that affect the load distribution. Furthermore, pressurized washers can reduce the stress distribution with any fibre orientation. Other numerical studies done by Mandal, B, et.al.[40] have conducted numerical studies for failure assessment of multi-bot FRP composite joints with varying sizes and preloads of bolts, see figure 6. 3D finite element mode developed by authors to investigate the fractures of double lap multi bolt FRP joint with various of bolt diameters, and tightening torques. The research works has done excellently with further comparison to literature available experimental results. Authors claim that the fracture load, Joint load, damaged load increase with increase of bolt diameter and bolting torque. However, the failure likely to in net-section instead of bearing failure.

Instead of observation on the mechanism of materials, more practical research like tying capacity of bolting important to be studied. Tying capacity is essential capacity to resist accidental loads in structure. In the past, no experimental study conducted to tying capacity specially for beam and column joints configuration until year 2015, Qureshi, et.al. [7] conducts tensile experimental studies on pultruded FRP web cleats on beam to column joints, see figure 7. Result shown tested FRP structures exceed the ASCE standard requirement which reveals of conservative suggestion in design standard. Moreover, Non-linear cracking failure observed to be 80% of its ultimate load. The authors propose new closed-form equation for a more accurate design reference compare to ASCE standards.
Figure 7. Numerical test on double-lap multi-bolt composite joint. (From Mandal, B, et.al., 2018)

Figure 8. General test arrangement for tension pull test (From Qureshi, et.al., 2015)

Figure 9. Detail A (From Qureshi, et.al., 2015)
In comparison of all reviewed papers, research works done in bolted connection for pultruded FRP is a recent popular topic. Challenges to the current design standard with close-form equation, numerical studies, experimental studies are published in recent years. Nevertheless, this is a sign of lack of accurate design details in bolted connection for pultruded FRP structures which may alarm for design practitioner to design with pre-caution. Additionally, the topic may provide plenty of space for future research.

5. Local & Global Buckling Design of Pultruded FRP Structures
Pultruded FRP structural members contains profile form by thin plates with both closed or open cross section. Pultruded FRP have higher longitudinal elasticity modulus and lower transverse elasticity modulus. Unlike steel structure, FRP structure members consists of non-uniform reinforcement. Global buckling capacity alone may be inaccurate to be addressed without looking into pre-buckling of local cross section details. Therefore, detail design shall often involve local and global buckling. In recent studies, plenty of experimental investigation and numerical studies conducted to the local and global buckling [41]–[45]. There were limited studies on built-up pultruded FRP structure system especially interaction between global and local buckling in the past. Boscato, et.al. [22] conduct both experimental and numerical studies on pultruded FRP local and global buckling interaction, as well as the influence of connecting pattern and shear deformation effect. Authors claim that pultruded structure system significantly influenced by interaction between local and global buckling. Further recommendation by Boscato, et.al, that non-linear analysis is better in analysing the interaction between local and global buckling of pultruded FRP structure system.

Often, structural designer prefers to ease their calculation work by simplified closed-form equation. In fact, the proposed closed-form equation by different researchers and manufacturers are not achieve single consensus equation. Lack of evaluation to their proposed closed-form equations may lead to application technical issues. Moreover, complex proposal such as lateral torsional buckling with geometrical imperfection studied by Nguyen, et.al. [43] and imperfection sensitivity in pure compression studied by Laudiero [27] are not effective in structure design application. In year 2018, Zhan, Y. et.al. [41] developed two closed-form equations approach to define reduction factor and initial imperfections factor for buckling studies of pultruded FRP structures by reviewing all published experimental database from year 1969 to 2016. Authors argue the weakness and limitation from the past available closed-form solutions. New developed closed-form equations proposed by Zhan, Y. et.al. well address flexural buckling capacity and imperfection factors used for design, see equation (1).

$$P_z = P_{c} / \left[1 + 0.04\sqrt{\beta P_{c}/(G_{LT}A_{g})} + P_{c}/(2N_C)\right]$$

Another view of imperfection factors, Ascione, et.al. [25] relate imperfection in a geometrical non-linear 1-dimensional model to analyse pultruded FRP structure. This approach able to predict pre-buckling of pultruded FRP structure effectively. More recent studies to redraw the close-form equation to predict pre-buckling and imperfection has been done effectively. Existing standard guideline often used conservative approach such as discrete plate analysis for local buckling design. Proposed analysis approach in European code have complex method to follow, may not be easy for quick calculation of critical buckling load. Cardoso & Vieira, [24] suggest explicit equation of critical local buckling for thin wall pultruded FRP structures based on Rayleigh Quotient energy method. Authors further argue that previous approach as conservative method and failed to reflect actual local buckling behaviours. However, no support to the mathematical model by any further experimental validation and numerical test done in the work.

In comparison of all reviewed papers, research works done in argument of unsatisfactory of current design standard practice. The complex closed-form equation proposed by current design standard are mainly ineffective. Plenty research works are suggesting simpler closed-form mathematical equation. Relatively lesser of experimental work and numerical work to justify the proposal of mathematical
model by different researchers. This is one of the future challenges to consolidate simple form of mathematical equation for design practitioner.

6. Conclusion
In conclusion, this paper has reviewed the recent studies in four major popular topics of pultruded FRP structural design in civil engineering. The environmental impact to the FRP material is important to be studied to know the fitness of serviceability. Research finding shows that high alkaline condition is significant in degrade the mechanical properties especially with elevated temperature. Thermal effect is significant affecting FRP properties during soaked conditions with freshwater or saltwater, while in dry condition, the thermal effect is less significant. Natural ageing such as temperature, freeze-thaw cycle, humidity and UV radiations are significant. However, the correlation is unclear and require for more research done in this area. The research for the environment impact are generally less quantified data for structure design application. Light weight properties of pultruded FRP structures cause vibration serviceability issues due to lower weight to stiffness ration compare to steel. The fundamental governing vibration components mass, damping and stiffness are important to be analyzed during the structure design. Researchers suggest that torsional vibration and shear deformation to be included in studies of vibration. Combined static and dynamics studies are highly encouraged. In comparison of all reviewed paper of dynamics response, there are less recent studies using experimental setup and less practical closed-form equation developed to represents vibration behavior in pultruded FRP structures. The closed-form equation which relates to various parameters could ease for design practitioner to perform design calculation in dynamics. For the topics of bolted connection, research works done in bolted connection for pultruded FRP is a popular topic. Plenty of new challenges published in correcting design standard with new close-form equation, numerical studies, and experimental studies. Nevertheless, this is a sign of lack of accurate design details in bolted connection for pultruded FRP structures. For the buckling issues, both interaction of local and global buckling design shall be included in pultruded FRP structures. In another hand, the structure imperfection is often included in the buckling research. In comparison of all reviewed papers, research works done often include argument of unsatisfactory of current design standard practice. This is mainly due to use of ineffective complex closed-form equation. Plenty of research works are suggesting simpler closed form equation. This is one of the future challenges to move toward research work in forming practical simple closed-form equation for more effective structural design application.

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