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Numerical analysis on the buckling behavior of pultruded GFRP members: a Systematic Review

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Abstract. This paper provides an overview of studies on the numerical investigations involving pultruded Glass Fiber Reinforced Polymers (pGFRP) members, bringing in light the current knowledge about numerical simulations using Finite Element (FE) method of pGFRP construction structures. Since the structural behavior of pGFRP members are governed by buckling phenomena, this paper is fully devoted to review studies involving instability problem. To achieve this purpose, we used a systematic review process to investigate the digital libraries and to document the review process. The main findings from this systematic literature review are presented and discussed. The results indicated that the number of studies involving numerical simulations of pGFRP structural members has been increasing in the last years and models more refined have been proposed, however some aspects are still a not a consensus among researches and others required more investigations.

Keywords: pultruded Glass Fiber Reinforced Polymers, numerical analysis, buckling, systematic review.

1 Introduction

The use of pultruded Glass Fiber Reinforced Polymer (pGFRP) material in construction industries has gained increasing acceptance due to its promising physical and mechanical properties. Despite the development of theoretical studies on the structural behavior of pGFRP members, the complex mechanic response of the composite materials makes their design challenging. pGFRP composite profiles are usually designed as perfect structures. Most of design codes considerer simplified assumptions and rough approximations about the loading, support conditions, and geometry. Nevertheless, as many studies have shown, different types of imperfections may occur, including material and geometric imperfections resulting from the manufacturing process, imperfections caused by load eccentricity or those related to boundary conditions. Due to the complex material behavior of composites, finite-element modeling becomes a powerful tool that consistently predicts the mechanical response of pultruded structural member without having to conduct numerous laboratory tests.

Development of many experimental and analytical studies on the buckling phenomena of pGFRP members have been motivated by the high deformability and proneness to instability of these members. Due to their intrinsic orthotropy and brittleness material behavior, the complexity of computational models that describe the constitutive stress–strain laws is much higher than those of isotropic ductile materials, as steel. This complexity underpins the widespread absence of reliable numerical studies on the advanced computational models of pGFRP members involving non-linear variables like initial geometric imperfections e progressive failure mechanisms. Furthermore, among the available numerical studies, it is noted that some procedures and parameters are not yet a consensus, resulting in a wide variety of methodologies used.

This paper aims to provide an overview on the studies that present numerical investigations on the instability behavior of pGFRP members, bringing to light the current knowledge in literature about numerical analysis of pGFRP profiles in construction structures. A systematic methodology is proposed to find, to select and to extract information from these studies. The main aspects regarding model geometry, materials properties, loads, boundary conditions and methods of analysis are compiled and discussed.

2 Search method

The systematic review was conducted in three well-defined phases: planning, conduction and data extraction. An overview of search method, as well, the main steps related to each phase are presented in Fig. 1.

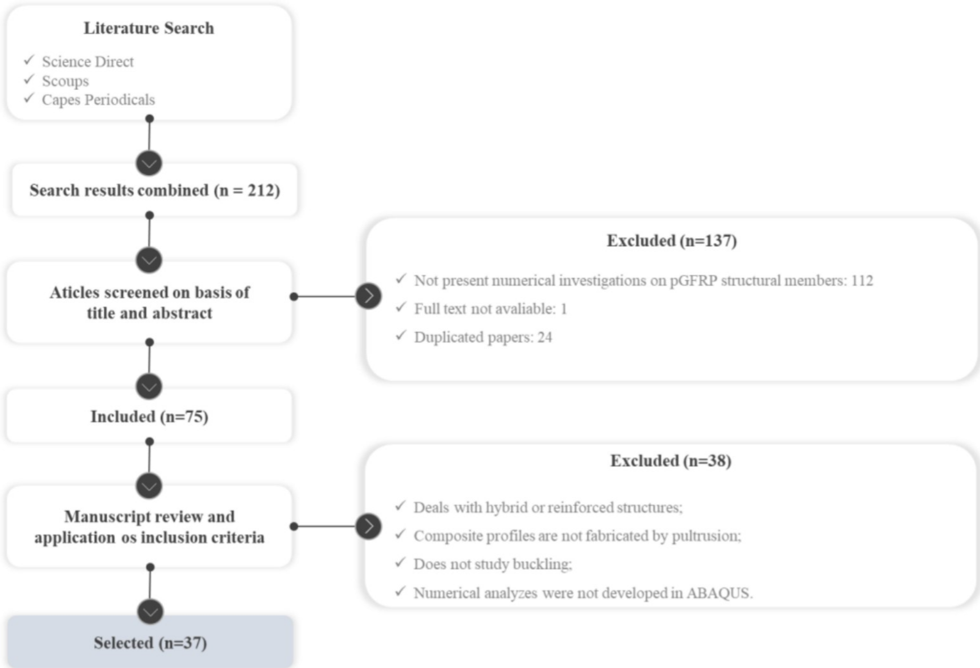

Figure 1. Flow diagram summarizing the selection studies stage

In the planning phase, a protocol was defined specifying the questions that motivate our study and the methodology to be employed in the conduction phase, specifically: (i) the criteria applied for inclusion or exclusion of studies; (ii) the scientific databases selected as reference sources; and (iii) the keywords used to construct the search string. Conduction and data extraction stages are described in the following topics.

2.1 Search Strategy and Data Sources

Since this paper aims to identify the state-of-the-art in relation to the existing knowledge concerning numerical simulation process of pGFRP profiles, the following questions were formulated in the protocol: “How has numerical simulation been used to study the mechanical behavior of pGFRP members?”; “What are the main aspects related to the physical and mechanical behavior of pGFRP members that should be considered in simulation models?” and “Is it possible to establish a standard procedure for numerical modeling of profiles subjected to buckling?”. To answer the specified questions, the selected string had been chosen: pultruded AND (column OR columns) AND buckling AND (“numerical analysis” OR “numerical simulation” OR “numerical results”) AND ABAQUS. Based on our experiences, we consulted databases that traditionally published articles on the subject: Science Direct. Scopus and Capes Periodicals.

2.2 Study Selection

The searches were carried out between May and August 2021. In total, 212 studies were retrieved, of which 92 were in the Science Direct database, 83 in the Scopus library, and 37 from the Capes Periodicals. The papers were downloaded into the systematic bibliography review manager Start and 24 duplicated papers were removed.

The resulted articles were screened and filtered in two rounds. In the first round, all the unrelated articles were excluded by checking the titles and abstracts. After this stage, 75 papers were selected. In the second round, full text was analyzed based on inclusion and exclusion criteria. The adopted inclusion criteria are as follows: (a) papers written in English or Portuguese; and (b) papers that report results and methods of numerical analyzes involving buckling performed in ABAQUS. The paper was excluded if: (d) is focused on hybrid structures (e.g., pultruded-concrete, pultruded-steel, pultruded-wood or others) or reinforced structures; (e) composite profiles are not fabricated by pultrusion; (f) not studying buckling; or (g) numerical analyzes were not developed in ABAQUS. A total of 37 papers (Table 1) met all the inclusion criteria and none of the exclusion criteria, therefore, they were selected in the second round.

Table 1. List of the papers select

Title	Year of publication
A closed-form equation for the local buckling moment of pultruded FRP I-beams in major-axis bending	2016
Analysis for creep behavior and collapse of thick-section composite structures	2006
An experimental and numerical study of the behaviour of glass fibre reinforced plastics (GRP) short columns at elevated temperatures	2004
A numerical and experimental study of the material properties determining the crushing behaviour of pultruded GFRP profiles under lateral compression	2013
A Simplified Design Method for Lateral Torsional Buckling of GFRP Pultruded I-Beams	2021
Assessment of FRP pultruded elements under static and dynamic loads	2018
Axial compression behaviour of all-composite modular wall system	2021
Buckling of advanced composite prestressed units under inplane loading	1996
Developing an innovative curved-pultruded large-scale GFRP arch beam	2021
Effect of eccentric loading on the stability and load-carrying capacity of thin-walled composite profiles with top-hat section	2020
Effect of load eccentricity on the buckling of thin-walled laminated C-columns	2018
Elastic flexural local buckling of Litzka castellated beams: Explicit equations and FE parametric study	2019
Enhancing flange local buckling strength of pultruded GFRP open-section beams	2020
Exact lateral buckling analysis for thin-walled composite beam under end moment	2007
Experimental and numerical study on the structural behavior of eccentrically loaded GFRP columns	2013
Finite element analysis of composite materials using abaqusâ„¢	2013
First-order, buckling and post-buckling behaviour of GFRP pultruded beams: Part 2 numerical simulation	2009
GBT buckling analysis of pultruded FRP lipped channel members	2003
GBT formulation to analyse the buckling behaviour of FRP composite open-section thin-walled columns	2010
GBT formulation to analyse the buckling behaviour of thin-walled members with arbitrarily 'branched' open cross-sections	2006
Generalised Beam Theory formulation to analyse the post-buckling behaviour of FRP composite thin-walled members	2006
Influence of boundary conditions and geometric imperfections on laterala torsional buckling resistance of a pultruded FRP I-beam by FEA	2013
Lateral buckling of pultruded GRP I-section cantilevers	1995
Modelling hollow pultruded FRP profiles under axial compression: Local buckling and progressive failure	2021
Progressive Damage Analysis of Web Crippling of GFRP Pultruded I-Sections	2017
Residual strength testing in pultruded FRP material under a variety of temperature cycles and values	2015
Shear-flexible thin-walled element for composite I-beams	2008
Simplified approach to estimate the lateral torsional buckling of GFRP channel beams	2021
Simulation of fire resistance behaviour of pultruded GFRP columns	2019
Stability and failure characterization of fiber reinforced pultruded beams with different stiffening elements, part 2: Analytical and numerical studies	2019
Stability performance of thin-walled pultruded beams with geometric web-flange junction imperfections	2021
Structural behavior of hybrid FRP pultruded beams: Experimental, numerical and analytical studies	2016
Structural behaviour of hybrid FRP pultruded columns. Part 2: Numerical study	2016
Test on pultruded GFRP I-section under web crippling	2015
Tests on GFRP Pultruded Profiles with Channel Section Subjected to Web Crippling	2017
Virtual characterization of delamination failures in pultruded GFRP angles	2016
Web crippling behavior of pultruded GFRP rectangular hollow sections	2015

2.3 Data Extraction and Synthesis

Data extraction and synthesis stage were duly documented based in a data extraction form including details of the to the bibliographic and reference information, a summary of the study and documented topics of interest were included. The main topics of interest extracted included: scope of study and modelling technique, FE and mesh adopted, mechanical model, numerical analysis and model validation procedure.

3 Results and Discussion

Figure 2 gives an overview of the 37 studies selected according their publication date. The first paper we identified was in 1995. Brooks and Thrvey [1] used ABAQUS finite element analysis to compute the critical lateral buckling loads of the pGFRP I-section cantilever. Although this study is very simple, comprising only the eigenvalue analysis, authors have already reported the need to incorporate the initial deformations in an incremental finite element analysis in order to obtain a closer correlation with the test results.

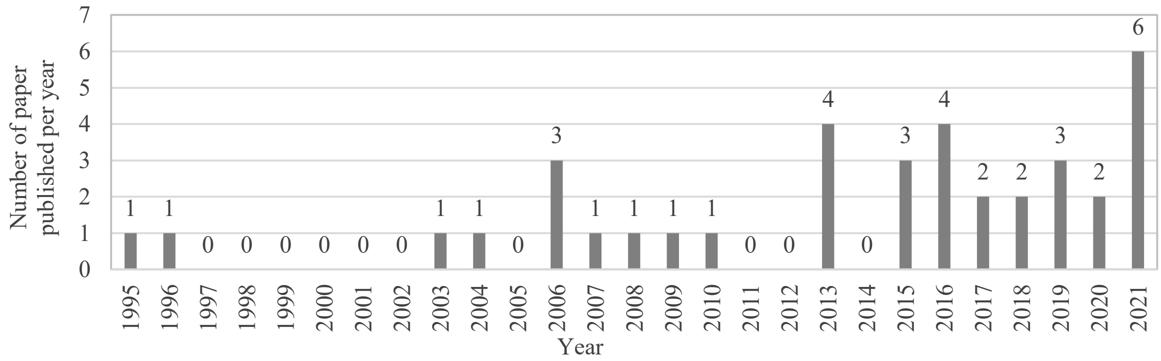

Figure 2. Number of papers published each year

Figure 2 shows that since 2013 there has been an increase in the number of works published, with the number of works already published in 2021 surpassing the number of any other year. The data presented in Figure 2 indicate that this field of research is in full expansion. In the following subsections, an overview of the state-of-the-art in relation to the main steps in the development of numerical modeling is presented based on the studies included through the RS.

3.1 Scope of studies and modelling techniques

In order to identify the key issues that have motivated the development of the numerical study presented in each paper, we extracted and analyzed the issues claimed to be addressed by the developers of the reviewed approaches. With regard the main(s) objective(s) of the paper, we classified the found issues into 11 groups ("a" to "k") as follows: (a) validation of a proposed design equation (6); (b) evaluation of failure modes (3); (c) fire behavior study (2); (d) buckling under dynamic load study (2); (e) buckling under static load study (8); (f) buckling under eccentric load study (3); (g) validation of a proposed numerical model developed with another software (5); (h) evaluation of design equations available in codes (4); (i) validation experimental results (1); (j) material defects study and (k) expand database. In parentheses, the number of works included in each group is shown. Note that the sum of the number of works is greater than 37. This is because some studies were included in more than one group.

3.2 Types of Finite Elements and Mesh stud

The level of detail necessary for description of the deformation and stress of composites depends on the level of post-processing desired. pGFRP composite material is commonly analyzed as a homogeneous equivalent shell. According to Barbero [2], this simple description of the composite material is sufficient when only displacements, buckling loads and modes are required. Table 2 summarizes the types of shell elements used to modeled pultruded composite profile in the articles selected. Note that the sum of the number of works is note equal to 37. This is because some authors tested more than one shell element. Three papers do not inform the element finite used.

Shell elements are used to model structures in which the thickness is significantly smaller than the other dimensions and the stresses in the thickness direction are negligible. Two types of shell elements are available in Abaqus: conventional and continuum shell elements. Conventional shell elements discretize a reference surface by defining the element's planar dimensions, its surface normal, and its initial curvature. Continuum shell elements, on the other hand, resemble 3D solid elements in that they discretize an entire three-dimensional body yet are formulated so that their kinematic and constitutive behavior is similar to conventional shell elements. For continuum shell elements, the First-Order Shear Deformation Theory (FSDT) constraints are enforced by special interpolation functions.

Three types of conventional shell are available: thin-only, tchick-only and general-purpose shell elements. Thin-only shell only enforces the Kirchhoff constraint, as opposed to thick-only shell elements that only enforce the FSDT constrains. Thin and thick-only elements provide for arbitrarily large rotations but only small strains, whereas the general-purpose shells account for finite membrane strains and arbitrarily large rotations. As thick-only shell element, general-purpose also includes transverse shear deformation through FSDT. Since in thin shell elements the transverse shear deformations are assumed to be zero, according to Barbero [2], they are not the best option for composites (even when b/t ratio are high), because their transverse shear moduli are small, therefore shear deformations may be underestimated.

Table 2. Main characteristics of shell elements used in the selected papers

Element	Type	Nodes	DOF	Description	Nº
S4	General purpose	4	$u_x, u_y, u_z, \theta_x, \theta_y, \theta_z$	Conventional shell	3
S4R	General purpose	4	$u_x, u_y, u_z, \theta_x, \theta_y, \theta_z$		9
S4R5	Thin-only	4	$u_x, u_y, u_z, \theta_x, \theta_y$		7
S8R	Thick-only	8	$u_x, u_y, u_z, \theta_x, \theta_y, \theta_z$		5
S8R5	Thin-only	8	$u_x, u_y, u_z, \theta_x, \theta_y$		1
S9R5	Thin-only	9	$u_x, u_y, u_z, \theta_x, \theta_y$		3
C3D8	Linear brick	8	$u_x, u_y, u_z,$	Solid	1
C3D8I	Linear brick, incompatible modes	8	$u_x, u_y, u_z,$		1
C3D8R	Linear brick, reduced integration, hourglass control	8	$u_x, u_y, u_z,$		2
C3D20R	Quadratic brick, reduced integration	20	$u_x, u_y, u_z,$		1
SC8R	General purpose	8	$u_x, u_y, u_z,$	Continuum shell	7

Solid elements do not assume any assumption of shell theory. They can be used for detailed analysis in regions where a rapid variation of stress and strain is expected. But, due to aspect ratio limitations a solid element with the thickness of a lamina should not have the other two dimensions larger than about 10 times the thickness. This would lead to a very refined mesh that would result in a computationally expensive solution.

Concerning the mesh, although some authors believe that for pultruded members a rectangular geometry with aspect ratio of 2:1 should be applied (due to unidirectional behavior), all papers (that presented information about the mesh adopted) evaluated in this work used quadrilateral mesh with 1:1 aspect ratio. In these papers, the mesh size adopted remained between 5 mm and 10 mm. The main criterion for the choice (calibration) of the mesh was the comparison of critical buckling loads.

3.3 Mechanical model and damage

Pultruded GFRP composite are characterized by an orthotropic behavior and brittleness. This material is normally modeled in ABAQUS as a transversely isotropic lamina defined by five elastic constants (Young's modulus in the 1 and 2 directions, shear modulus in the 12, 13 and 23 planes and Poisson's ratio in plane 12) and six strength properties (tensile, compression and shear strengths in the longitudinal and transversal directions). Directions 1,2 e 3 are related do longitudinal in-plane direction, transverse in-plane direction and transverse out-of-plane direction, respectively.

Strength properties are only required when damage evolution analysis will be performed. This type of analysis is important to accurately predict the ultimate load of the columns (since allows accessing the column post-buckling behavior) and taking into account material non-linearities that often lead the column to premature failure. Among the papers selected in this SR, only 11 evaluated the material damage. Material damage of fiber reinforced composites in ABAQUS is considered through Hashin damage model. In this model, the progressive failure is based on the method proposed by Lapcyk e Hurtado [3], damage properties follows the degradation Matzenmiller et al. [4] methodology and damage initiation is governed by Hashin failure criteria.

Hashin damage model considered that the increase of damage is governed by equivalent displacements that are calculated during the damage process from dissipated fracture energies (G) defined for each failure mode. Since fracture energy evaluation for pGFRP material is not yet standardized, different strategies have been adopted to define it. Amongst the procedures presented in the selected papers, the following ones may be mentioned: (i) to perform non standardized tests; (ii) estimating G as the area under the stress vs. strain curves obtained from the mechanical characterization; and (iii) using literature review data. From the papers evaluated in this SR, fracture energy fiber tension (G_{ft}) , fracture energy fiber compression (G_{fc}), fracture energy matrix crack (G_{mt}) and fracture energy matrix crush. (G_{mc}) varied from 2.38 to 92, 5.28 to 79, 0.424 to 5,0.948 to 20, respectively. As ca be noted the values are quite variable.

According to Azevedo [5], there is still no consensus in the scientific community regarding the fracture energies of the GFRP material. The author reports that the few works published so far refer to carbon composites and epoxy matrix; and states that the reported values have high variability. In addition, Azevedo [5] highlights that an experimental program has not yet been carried out in order to certify the values available in the literature. Our SR confirmed the conclusions of Azevedo [5]. To fully understand the state-of-the-art damage mechanics analysis of pultruded members, other papers dealing with numerical analysis of pGFRP profiles were consulted. This additional literature review confirmed the wide variability of G (which ranged between 200 and less than 1) and lack of a solid theoretical and/or experimental basis for the assumed values.

Most likely, the spread use of the Hashin-based damage analysis has been hampered by the large amount of material data required, such as strengths, fracture energies and viscous regularization parameters, which are often not reported by manufacturers [6]. Another data required by Hashin damage model are the viscosity coefficients for the four failure modes considered in Hashin failure criteria (namely, matrix and fiber compression and tensile failure). These parameters improve convergence problems in the softening regime. Commonly, the same value is considered for all failure modes and it remain in the range of 10^{-3} to 10^{-5}.

3.4 Numerical analysis

It is observed that numerical buckling analysis have been performed in literature using four approaches: (i) linear eigenvalue analysis; (ii) nonlinear analysis taking into account initial imperfections; (iii) nonlinear analysis considering material damage; and (iv) nonlinear analysis assuming both nonlinearities (initial imperfections and damage).

The linear eigenvalue buckling analysis has been extensively used in literature to study instability behavior of pGFRP profiles. Besides simplicity and low computational requirement, this method may provide good predictions. Due to the brittle behavior of reinforced composites, in theory, they tend to remain in linear-elastic regime for large levels of stresses and strain, so that critical buckling load could be directly estimated as the ultimate load. Nevertheless, in this type of analysis the results can be highly affected by geometry and material characteristics. Several studies have been proven that geometry and material imperfections should be relevant to obtain accurate predictions. Furthermore, linear analyses cannot capture nonlinear geometry, post-buckling, and progressive failure behavior.

Non-linearity in pGFRP members comprehends material (damage) and geometric (initial imperfections) non-linearity. Initial imperfections are univariably in real columns affecting their buckling behavior. This non-linearity can alter considerably the post-buckling behavior and strength of the pGFRP, specially for columns that are prone to buckling mode interaction. In the numerical studies evaluated in this RS, initial imperfections were commonly computed imputing a deflection in the middle of the member or assuming the deformed shape of the first buckling load affect by a reduction factor. It was noted that the amplitude of this imperfection is considerably variable and the values adopted are not from measurements. In fact, there is a lack of studies on the characterization of the geometric imperfections of pGFRP, which makes it difficult to define a range of consensual values. Values between L/2000 and L/240 (adopted in numerical simulations) and L/8053 and L/586 (measured dimension) can be found in literature. Measured values are essentially comprised by out-of-straightness of I-sections.

Finally, physical nonlinearity allows one to model the problem response for stress levels beyond the linear-elastic regime. In the case of pGFRP composites, which have a brittle behavior, these voltage levels correspond to the degradation of the material. As discussed previously, material progressive failure analysis is still been developed in pGFRP instability studies and more studies are required.

3.5 Model validation

Since material characterization of composites is not a simple task and experimental results are not always available, model validation needs special attention. Besides the complexity of material behavior, defining mesh, constrains and other parameters is also an important step for reliable models. Establishing the accuracy of the finite element model is essential before it is used for the analysis.

The validity and accuracy of the FE models proposed in the selected papers were usually assessed comparing FE results against theoretical (analytical formulae or another simulation software) and experimental data in terms of the load capacity. In general, the validation of eigenvalue analysis includes comparations with critical loads obtained from analytical expressions and/or GBTul software. Non-linear results are commonly verified based on experimental data (majority ultimate loads) obtained from tests performed by the authors or reported in literature. A smaller number of studies have compared load–displacement curves and/or failure modes obtained in numerical simulations to their experimental counterparts.

4 Conclusions

In this paper, we present the results from a Systematic Review (SR) on the state-of-the-art of the numerical studies on pultruded Glass Fiber Reinforced Polymers (pGFRP). Our study aimed to find researches that used the Finite Element method through the ABAQUS software to solve instability problems in pultruded structural members. Since the use of pGFRP members in civil engineering structures is relatively recent, we believe that the data presented in this paper provide interesting insights into the current status of numerical modelling research, besides to support the development of numerical analysis by engineers who are not well acquainted with pultruded employment applied to civil structural designs. This SR has also identified certain gaps that need to be filled by future research. This SR has enabled us to make the following:

i. S4R and SC8R are the most popular types of elements used in the numerical studies analyzed. Results presented in the papers analyzed showed that reduced integration considerably reduced the execution time of simulation, without compromise the accuracy of the results obtained, as long as the finite elements are requested only according to the average surface and do not exhibit significant distortions;
ii. the adopted values of fracture energy for pGFRP materials are still uncertain (scarce and highly variable) and further studies are needed to obtain more data related to this parameter;
iii. there is still an absence of studies that take into account all the nonlinearities (material and geometrical) that influence the pGFRP structural member behavior, indicating the need to develop reliable and consistent models;
iv. from the studies included in this review, it is observed that the most explored subject is the study of the buckling behavior of pGFRP members under static loads, which indicates that mechanical behavior of theses structural members is being still being understood by researchers.

Finally, the growth in the number of papers published in recent years (especially in the current year) indicates that the field of research is on the rise and that new findings should continue to be made in the coming years, promoting the advancement of numerical research on pultruded profiles

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