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ADVISORY COMMITTEE
ON TECHNICAL RECOMMENDATIONS FOR CONSTRUCTION

Guide for the Design and Construction of Structures made of FRP Pultruded Elements

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1 FOREWORD

The present document adds to the series of technical documents recently issued by the National Research Council of Italy (CNR) on the structural use of fibre-reinforced polymer (FRP) composites, started with the publication of CNR-DT 200/2004.
The documents published so far have dealt with: the design and construction of externally bonded FRP systems for strengthening existing reinforced and pre-stressed concrete structures and masonry structures (CNR-DT 200/2004), the strengthening of timber structures (CNR-DT 201/2005) and metallic structures (CNR-DT 202/2005), the use of FRP bars for replacing steel ones within reinforced concrete members (CNR-DT 203/2006) and finally the use of reinforced concrete with the addition of steel fibres, polymeric and carbon material which can be added either as normal or pre-stressed strengthening bars (CNR-DT 204/2006).
Over the last 15 years, in Europe and not only, several pioneering solutions have clearly shown the usefulness of FRP in new structures. These solutions were often driven by various factors including quickness of assembly and resistance to aggressive environments, the latter reducing maintenance costs. While the lightness of FRPs makes assembly and construction easier, the low weight also gives an advantage to structures built on soft ground.
The increasing demand for design solutions which use FRP pultruded elements lead to the adoption on a national level of the European regulations EN 13706-1, EN 13706-2 and EN 13706-3 in 2003. These regulations define the minimum requisites for classifying pultrudes as “structural”. Therefore, the drawing up of a guide for the design and construction of structures with elements obtained through the technique of pultrusion and made of organic resins strengthened with glass fibres (GFRP) became indispensable.
The approach adopted here is the semi-probabilistic limit state method, the same as in the Eurocodes which divides the propositions into “principles” (denoted with the letter P) and “application regulations”.

This document also has four Appendices:
Appendix A – Further study on the critical load of local instability of double T stressed pultrudes;
Appendix B – Production techniques of FRP pultrudes;
Appendix C – Typical technical data sheet of FRP pultrudes; material characterisation tests;
Appendix D – Choice and verification of FRP pultrudes: duties and responsibilities of the designer.

The main aim of the document CNR n.205/2007 is to spread within the Technical-Professional community the knowledge acquired on the FRP pultruded elements the design and construction of new structures.
This document deals with structures made of FRP pultruded elements. The most common reinforcing fibres are glass, carbon and aramid. Current applications in the field of civil engineering generally use glass fibres, with specific reference being made to them in this document. Fibres not only give pultrudes an elastic behaviour up to failure but they also make them highly orthotropic, with increased stiffness and resistance in the fibre direction. Orthotropic properties notably influence the phenomena of local instability as well as the interaction between local and global instability. The proposed analysis models assume a constitutive elastic-linear behaviour of FRP, while the verification models are based on resistance models, even in the case of instability. The design regulations take into consideration the state of the experimental knowledge still currently being developed. Therefore, in the case of double symmetrical sections, they are based on analytical expressions, while in other cases on numerical procedures.
This document is not a binding set of regulations but it merely represents an aid for practitioners

interested in the field of FRPs. Nevertheless, the responsibility of the choices remains with the designer.
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1.1 PUBLIC HEARING

This Technical Document has been approved by the “Advisory Committee on Technical Recommendations for Construction” as a draft version on 24/09/2007, and as final version on 09/10/2008.
This latter document includes the modifications and/or integrations derived from the public hearing.
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1.2 SYMBOLS

The following symbols are used in this document.

General notions

$(.)_b$ value of quantity (.) related to the bolt
$(.)_d$ design value of quantity (.)
$(.)_f$ value of quantity (.) related to the flange of the pultruded element
$(.)_k$ characteristic value of quantity (.)
$(.)_L$ value of quantity (.) related to the longitudinal direction
$(.)_{loc}$ value of quantity (.) related to the local instability
$(.)_{max}$ maximum value of quantity (.)
$(.)_{min}$ minimum value of quantity (.)
$(.)_R$ value of quantity (.) as resistance
$(.)_S$ value of quantity (.) as load
$(.)_t$ value of quantity (.) related to tension
$(.)_c$ value of quantity (.) related to compression
$(.)_T$ value of quantity (.) related to the transversal direction
$(.)_w$ value of quantity (.) related to the web of the pultruded element

Upper case Roman letters

A cross-section area of the pultruded element
A_b resistant area of the section of the bolt
A_{net} cross-section area of the pultruded element minus the area(s) of the holes
A_V area of cross-section resistant to shear
E_{eff} effective modulus of elasticity
E_{Lc} longitudinal modulus of elasticity in compression
E_{Lt} longitudinal modulus of elasticity in tension
E_{Tc} transversal modulus of elasticity in compression
E_{Tt} transversal modulus of elasticity in tension
$F_{Tt,Rd}$ design value of the tensile strength of the bolt
G_{eff} effective shear modulus of elasticity
G_I fracture energy for mode I
G_{II} fracture energy for mode II
G_{LT} shear modulus of elasticity within the plane LT
J_{min} moment of inertia (minimum value)
J_t torsional stiffness factor of the section
J_ω warping stiffness factor of the section
L length or distance between two consecutive flexural-torsional restraints
L_0 buckling length
L^* length of the bonding
M_{eq} equivalent bending moment value
M_{FT} bending moment value which provokes flexure-torsional instability
M_m average bending moment value
M_{max} maximum bending moment value
$M_{loc,Rd}$ design value of the bending moment which provokes the local instability of the pultruded element
M_{Rd1} design value of the resisting moment
M_{Rd2} design value of the bending moment which provokes the instability of the pultruded

element
M_{Sd} design value of the stressing moment
$N_{c,Rd1}$ design value of the compressive strength
$N_{c,Rd2}$ design value of the normal force which provokes the instability of the element
$N_{c,Sd}$ design value of the compressive load
N_{Eul} eulerian critical load
$N_{loc,Rd}$ design value of the normal force which provokes the local instability of the pultruded element
$N_{t,Rd}$ design value of the axial resistance
$N_{t,Sd}$ design value of the axial load
T_{Sd} design value of the stressing torque
T^{SV} primary or De Saint Venant torque
T^{ω} torque due to non-uniform torsion
V_x coefficient of variation
V_{Rd} design value of the shear resisting force
V_{Sd} design value of the shear stressing force
W modulus of resistance

Lower case Roman letters
c coefficient of interaction between local and global instability
d diameter of the hole
d_b diameter of the bolt
d_r diameter of the washer
e distance of the hole from the edge of the section in the direction of the applied force/moment
f_{Lc} or f_c longitudinal compressive strength
f_{Lf} longitudinal flexural strength
f_{Lr} longitudinal bearing strength
f_{Lt} or f_t longitudinal tensile strength
f_{Tr} transversal bearing strength
f_{Tc} transversal compressive strength
f_{Tf} transversal flexural strength
f_{Tt} transversal tensile strength
f_V shear strength
f_{Vb} shear strength of the bolt
f_{Rk} characteristic strength
$f_{V,loc,k}$ characteristic value of stress which provokes the local instability of the panel of the web
$f_{Sd,z}$ design value of compressive stress acting in transversal direction
f_{loc}^{axial} value of local critical stress for compressed elements
f_{loc}^{flex} value of local critical stress for elements under flexure
n number of the holes
s distance of the hole from the edge of the section in the orthogonal direction to the applied force
t thickness of the pultruded element
w distance between holes

Lower case Greek letters
χ reductive coefficient to be applied to the stress which provokes local instability

χ_{FT}	reductive coefficient to be applied to the bending moment which provokes local instability
δ	deflection
ϕ_E	coefficient of viscosity for longitudinal deformations
ϕ_G	coefficient of viscosity for shear deformations
γ_a	partial coefficient for the adhesive
γ_f	partial coefficient for FRP elements
γ_m	partial coefficient for materials or products
γ_{Rd}	partial coefficient for the resistance models
η	conversion factor
η_a	environmental conversion factor
η_l	conversion factor for long-term effects
λ	parameter of slenderness for pultrudes subjected to compression
λ_{FT}	parameter of slenderness for pultrudes subjected to flexure
ν_{LT}	Poisson’s ratio (longitudinal)
ν_{TL}	Poisson’s ratio (transversal)

2 CHARACTERISTICS OF FRP PULTRUDES

(1) FRP structural elements take the shape of thin profiles made from thermoset resins strengthened with long glass fibres by the technique of pultrusion (Appendix B).

(2)P The mechanical properties of these materials depend on the type of matrix, the type of fibre as well as their volumetric fraction.

(3) The pultrudes can be either bolted or bonded. All the materials used in the joints should have the same characteristics.

(4)P Determination of the mechanical properties requires specific procedures, when considering that, unlike traditional metallic elements, pultrudes are characterised by an overall, global orthotropic behaviour which can be translated into a transversal isotropic behaviour on the plane of the cross-section.

(5) The dimensional tolerance for pultrudes is generally indicated by the manufacturer. Appendix B of the regulations UNI EN 13706-2:2003 reports several dimensional tolerance values.

2.1 QUALITY CONTROL

(1)P The characterisation of a FRP product through appropriate tests is developed by the manufacturer with three specific aims:

- to guarantee quality and respect the minimum required values;
- to supply test results in a statistically significant number relative to the physical and mechanical characteristics;
- to supply additional information on the long-term behaviour.

(2) The physical and mechanical characterisation tests should be carried out by fully equipped certified laboratories, with all the required expertise as well as proven experience in characterising FRPs.

(3) Each manufacturer supplies a technical data sheet relative to the FRP pultrudes which indicates the values of the mechanical properties obtained from a statistical analysis and includes the characterising values upon which the corresponding failure modes are based. Appendix C shows a model of a technical data sheet with the most common characterisation tests.

2.2 ACCEPTANCE CRITERIA

(1) The FRP pultrudes to be used as structural elements for new constructions should be subjected to controls which guarantee an adequate level of the physical and mechanical properties.
Several notes relating to the processes of certification and acceptance of FRP pultrudes are schematically summarised in Appendix D, highlighting the responsibility and duties of the various operators.

3 BASIS OF DESIGN

(1) New FRP pultruded structures are dealt with in this chapter. The formulae, calculation procedures and application regulations are based on theories, numerical models and test results validated for thin-walled composite profiles.

(2) It can be assumed that:

- adequate supervision and quality control of the production process as well as the product shall be guaranteed;
- the choice of the structural elements and joints, as well as the design of the structure, shall all be carried out by qualified technicians and experts;
- the structure shall be realised by operators with an adequate level of knowledge and experience;
- the materials and products used shall be used as specified below.

3(P) The design of the structure should satisfy the resistance, service and durability requisites. In the case of fire, the resistance of the structural elements as well as the joints should be adequate for the exposure time that is required, introducing protection systems.

3.1 BASIC REQUIREMENTS

(1)P The design of the structure should take into account all the possible actions that could affect its service life. The risks to which it could be subjected to should be identified and, if present, either reduced or eliminated.

(2)P The basic requisites are considered satisfied when the following is guaranteed:

- an appropriate choice of materials;
- careful execution of structural details;
- definition of the appropriate procedures of design control, production, realisation and use.

3.2 SERVICE LIFE OF THE STRUCTURE

(1)P The service life is a design requisite and should be defined on the basis of the final function of the structure. The calculations should be those set out in the currently adopted regulations. In the case of a particular function, such as temporary structures, reference can be made to the regulations set out in UNI EN 1990 for the choice of the partial coefficients of the serviceability state.

3.3 DURABILITY REQUIREMENTS

(1)P The design of the structure should guarantee a constant performance over time, taking into account both the environmental conditions as well as the maintenance programme.

(2)P The environmental conditions should be identified during the design phase in order to evaluate their influence on the durability of the structure, with any eventual measures being included to protect the material.

(3)P In order to evaluate the performance of the structure in terms of its durability, theoretical

models as well as tests results and studies on the behaviour of similar structures reported in literature can be referred to.
(4) In order to guarantee the durability of the structure, the following should be taken into account:

- the function;
- the environmental conditions;
- the composition, properties and performance of the materials;
- the choice of the type of joints;
- the quality and level of realisation control;
- the planned maintenance during the service life.

5(P) Particular issues (environmental actions, loading manner) should be identified during the design phase, in order to evaluate their influence on the durability of the pultrudes.

3.4 GENERAL DESIGN PRINCIPLES

3.4.1 General

(1)P Verification of both elements and joints should be carried out in relation to both the serviceability limit states (SLS) as well as the ultimate limit states (ULS), as defined by the currently adopted regulations.

(2)P The partial coefficient method should be used to verify that none of the limit states are violated during all the design phases, adopting the calculated values of actions and resistance. The following limitation should be satisfied:

$$E_{\mathrm{d}} \leq R_{\mathrm{d}}, \tag{3.1}$$

where E_{d} and R_{d} are, respectively, the design values of the generic action and the corresponding capacity (in terms of resistance or deformation), within a generic limit state.

(3) The design values can be obtained from the characteristic values with appropriate partial coefficients for the various state limits, with the values of the currently adopted regulations being codified. In other words, they are indicated in this document with reference to the specific context.

3.4.2 Calculations

(1) The computed actions are set out in the currently adopted regulations, with reference to the service life of the structure.

3.4.3 Properties of the materials, elements and products

(1)P The values of the properties of materials, structural elements and products used for the joints should be determined by laboratory tests, such as those reported in Appendix C.

(2) The regulations UNI EN 13706:2003 define classes of GFRP pultrudes for structural use with the initials "EXX", where XX is the effective value of the modulus of elasticity in flexure in GPa. Reference can be made to the aforementioned set of regulations for the designation method of

structural pultrudes (UNI EN 13706-1) as well as for the test methods (UNI EN 13706-2). The mechanical properties of the pultrudes can be determined on either a sample of the element or the whole element. The minimum requisites (UNI EN 13706-3) which the pultrudes should comply to, at room-temperature, in order to be classified as structural, are indicated in Appendix C.
(3) The possible ways to carry out the mechanical characterisation tests on the pultrudes are reported in Appendix C.

(4) In verifying the resistance as well as the stability, it should be assumed that the characteristic values shall be less than 5%. In verifying the deformability, the mean values of the modulus of elasticity determined, for example, according to UNI EN 13706-2 can be introduced.

(5) The value, X_d, of the generic property of resistance or deformation of a material can be expressed, in a general form, through the following relation:

$$X_{\mathrm{d}} = \eta \cdot \frac{X_{\mathrm{k}}}{\gamma_{\mathrm{m}}}, \tag{3.2}$$

where η is a conversion factor which takes into account, in a multiplicative manner, the pecularity of the problem (§ 3.6), X_k is the characteristic value of the property and γ_m is the partial coefficient of the material.

(6) In (3.2), the conversion factor η is obtained by multiplying the environmental conversion factor, η_a, by the long-term effects conversion factor, η_l. The values attributed to these factors are indicated, respectively, in §§ 3.6.1 and 3.6.2. In alternative, values resulting from tests on prototypes can also be attributed to these coefficients.

3.4.4 Design capacity

(1) Design capacity, R_d, can be expressed as the following:

$$R_{\mathrm{d}} = \frac{1}{\gamma_{\mathrm{Rd}}} \cdot R\left\{X_{\mathrm{d,i}}, a_{\mathrm{d,i}}\right\}, \tag{3.3}$$

where $R\{\cdot\}$ is a function based either on the specific mechanical model considered or on a particular test (e.g. flexure, shear, critical load) and γ_{Rd} is a partial coefficient which takes into account the uncertainties of the resistance model or the test procedure. Unless otherwise stated, this coefficient is equal to 1. In relation to the function $R\{\cdot\}$, in general, there are classes of mechanical and large geometric properties, of which $X_{d,i}$ and $a_{d,i}$, represent, respectively, the design value and the generic nominal value.

3.5 PARTIAL COEFFICIENTS

3.5.1 Materials

(1) For the ultimate limit states, the partial safety coefficient of the material, γ_f, can be obtained using the expression:

$$\gamma_f = \gamma_{f1} \cdot \gamma_{f2}, \tag{3.4}$$

where γ_{f1} takes into account the level of uncertainty in the determination of the properties of the material, with the coefficient of variation V_x (Table 3-1). The value 1.30 could be attributed to γ_{f2} for the appropriate caution in relation to the fragile behaviour of the FRP.

Table 3-1 – Values of γ_{f1} versus the coefficient of variation V_x.

	$V_x \leq 0.1$	$0.1 < V_x \leq 0.20$
γ_{f1}	1.10	1.15

The value of V_x related to the characteristic value of the property of resistance or deformation of the material should be determined through an appropriate series of tests.

(2) In every case, it is possible to evaluate the structural safety through tests on either single elements or the whole system.

(3) For the serviceability limit states, a unitary value is suggested for the partial coefficient of the material, γ_f.

3.5.2 Joints

(1) For bonded joints with structural adhesives, the safety coefficient of the material, γ_a, can be expressed through the following:

$$\gamma_a = \gamma_{a1} \cdot \gamma_{a2} \cdot \gamma_{a3} \cdot \gamma_{a4}, \tag{3.5}$$

where the factors γ_{a1}, γ_{a2}, γ_{a3} and γ_{a4}, indicated in Table 3-2, take into account, in a multiplicative manner, the mechanical properties of the adhesive, the method of adhesive application, the load conditions and the environmental conditions, respectively.
In every case, values no less than 2 should be assumed for the coefficient γ_a.

(2)P For bolted joints, the value of the partial coefficient of the FRP elements, γ_f, for the ultimate limit states, should be determined according to the relation (3.4).

(3) In order to verify the single parts of the joints of different materials, the coefficient of the material, γ_m, should be determined in accordance to the currently adopted regulations or any other certified set of regulations.

Table 3-2 – Values of the partial safety coefficients γ_{a1}, γ_{a2}, γ_{a3} and γ_{a4} for adhesives.

Determination of the mechanical properties of the adhesive	γ_{a1}
Values supplied by the manufacturer	2
Values obtained from specific tests	1.25
Adhesive application method	γ_{a2}
Manual application with few controls of the thickness	1.5
Manual application with systematic control of the thickness	1.25
Identified application with defined and repeatable controlled parameters	1
Load combinations	γ_{a3}
Quasi-permanent combinations	1.5
Other combinations	1
Environmental conditions	γ_{a4}
Properties of the adhesive not evaluated in the service conditions	2
Properties of the adhesive determined in the service conditions	1

3.5.3 Resistance models

(1) A partial coefficient, γ_{Rd}, should be introduced for every resistance model as well as type of joint (bolted or bonded), even those made of different materials, in order to take into account the reliability of the model. In the case of design aided by tests, the coefficient of the model can be obtained in accordance to the procedures indicated in UNI EN 1990.

3.6 SPECIAL PROBLEMS AND RELEVANT CONVERSION FACTORS

(1) Several reference values which can be attributed to the conversion factor η, introduced in § 3.4.3, are reported. They can be used in order to determine the property of the calculations. They are divided in relation to the aspects which can influence either the durability or behaviour of a material under particular conditions.

3.6.1 Environmental conversion factor η_a

(1)P The mechanical properties (e.g. tensile strength, ultimate strain and elasticity moduli) of several FRP pultrudes can become degraded in the presence of specific environmental conditions: alkaline environments, dampness (water and saline solutions), extreme temperatures, thermal cycles, freezing and thawing cycles, ultraviolet radiation (UV).

(2) Protective coverings which not only mitigate the effects of exposure, but have already been tested and allow the service life of the structure to remain unaltered should be used in aggressive environments. The value of the coefficient η_a in the presence of adequate protective systems can be assumed to be equal to 1. In uncertain cases, the value of the coefficient η_a should be appropriately reduced, even in relation to the service life of the structure.

3.6.2 Conversion factor for long-term effects η_l

(1)P The mechanical properties (e.g. tensile strength, ultimate strain and elasticity moduli) of several FRP pultrudes can become degraded in the presence of rheological phenomena (viscosity, relaxation, fatigue).

(2) The rheological phenomena in FRP pultrudes depend on the properties of the matrix as well as the fibres. In particular, viscosity appears to be more contained with an increasing percentage of fibres, while static fatigue can be mitigated by limiting the level service stress.

(3) The values suggested for the conversion factor, η_l, relative to the failure of the FRP pultrudes under long-term stress and in the case of cyclic loading (fatigue) for GFRP pultrudes are reported in Table 3-3.

Table 3-3 – Values of the conversion factor for long-term phenomena, η_l, in the case of GFRP pultruded, for Ultimate Limit States and Serviceability Limit States.

Load type	η_l (SLS)	η_l (ULS)
Quasi-permanent	0.30	1.00
Cyclic Load (fatigue)	0.50	1.00

3.7 ANALYSIS CRITERIA

(1)P The analysis of the structural response should be carried out taking into account the elastic behaviour up to failure and, if necessary, the orthotropy of the materials. The stress on the structural elements and joints should be determined through a global analysis of the structure, considering, when relevant, the deformability of the joints.

(2) The second order effects should also be taken into account in the analysis, due to them being significant.

(3) The analysis of thin-walled FRP profiles with open section subjected to torsion should be carried out taking into account both the primary and the secondary torsional stiffness.

(4) For bolted joints, the strains of every single bolt should be evaluated taking into account the elastic properties of the structural elements connected to them. The verification should be carried out considering all the possible crisis modes of the joints.

3.8 VERIFICATION CRITERIA

(1)P The verification of resistance should be carried out considering the eventual simultaneous presence of more than one stress characteristic.

(2)P The verification of stability should take into account the eventual interaction between local and global instability phenomena. A local verification of the parts under compression should be carried out when the constraint conditions prevent global instability.

(3) In a quasi-permanent load combination, the verification of local and global stability should be carried out introducing reduced values for the elasticity moduli due to the effect of the viscous strain, as highlighted in § 6.2.

(4) In the case of design aided by tests, the design value of the property of interest (e.g. the design resistance capacity, R_d) can be obtained in accordance to the procedure indicated in UNI EN 1990.

(5) In the case of numeric modelling, the design value of the property of interest (e.g. the design resistance capacity, R_d) should be obtained from an incremental analysis which takes into account the imperfections, introducing the design values of the mechanical properties.

3.9 STRAIN EVALUATION

(1) Both the flexure deformability as well as the shear deformability should be taken into account in order to evaluate the deflection of the profiles under bending.

3.10 BEHAVIOUR IN THE CASE OF FIRE

(1)P FRP materials are highly sensitive to high temperatures. In fact, when the temperature of the FRP exceeds that of the glass transition of the resin, T_g,, the resistance and stiffness of the structural element are notably reduced.

(2) Under conditions of exposure to fire, the mechanical properties of the FRP can be significantly prevented from decreasing by either a covering of an appropriate thickness, or pultruded elements produced with special resins as well as active protection systems. Coverings and resins which reduce the spreading of the flames and amount of smoke can also be used.

(3) The exceptional load combinations indicated in the currently adopted guidelines should be used in the case of the structure being designed for an established exposure time.

4 VERIFICATION OF THE ULTIMATE LIMIT STATES OF THE PULTRUDES

4.1 NORMAL FORCE

4.1.1 Elements under traction

(1) In the case of structures subjected to axial tensile load, the design value of the force, $N_{t,Sd}$, should satisfy the following limitation:

$$N_{t,Sd} \le N_{t,Rd}. \tag{4.1}$$

In (4.1) the design resistance, $N_{t,Rd}$, takes the following values:

- (not-perforated section)

$$N_{t,Rd} = A \cdot f_{t,d}, \tag{4.2}$$

- (perforated section)

$$N_{t,Rd} = \frac{1}{\gamma_{Rd}} \cdot A_{net} \cdot f_{t,d}, \tag{4.3}$$

where $f_{t,d}$ is the design strength of the material, A is the area of the section, γ_{Rd} is the partial coefficient of the model, assumed equal to 1.11 and A_{net} is the net area of the section. The latter can be evaluated as follows:

$$A_{net} = A - n \cdot t \cdot d, \tag{4.4}$$

where n and d are, respectively, the number and diameter of the holes present, while t is the thickness of the pultrude.

4.1.2 Compressed elements

(1) In the case of elements subjected to axial compressive load, the design value of the compressive force, $N_{c,Sd}$, corresponding to each of the transversal sections, should satisfy the limitation:

$$N_{c,Sd} \le N_{c,Rd}. \tag{4.5}$$

In (4.5) the design resistance, $N_{c,Rd}$, can be obtained from the relation:

$$N_{c,Rd} = \min\left\{N_{c,Rd1}, N_{c,Rd2}\right\}, \tag{4.6}$$

where $N_{c,Rd1}$ is the value of the compressive force of the pultruded element and $N_{c,Rd2}$ the design compression value which provokes the instability of the element.
The value of $N_{c,Rd1}$ can be calculated through the following expression:

$$N_{c,Rd1} = A \cdot f_{c,d}, \tag{4.7}$$

where $f_{c,d}$ is the design compressive strength of the material.
The value of $N_{c,Rd2}$ can be determined either through tests (§ 3.8 (4)) or numerical/analytical modelling (§ 3.8 (5)).
In the latter case, the analysis can be carried out by attributing the pultruded element an initial imperfection. This imperfection can consist of a field of displacements proportional to the first critical mode, amplified according to the tolerance declared by the manufacturer and not less than that indicated in Appendix B of UNI EN 13706-2. The form of the first critical mode can be determined through approximated procedures.

(2) In the case of pultrudes with double symmetric section, the value $N_{c,Rd2}$ results equal to:

$$N_{c,Rd2} = \chi \cdot N_{loc,Rd}, \tag{4.8}$$

where the design value of compressive force which determines the local instability of the pultruded elements, $N_{loc,Rd}$, can be determined either through tests carried out on large beams (§ 3.8 (4)) or numerical/analytical modelling (§ 3.8 (5)). In alternative, it can be obtained from the following relation:

$$N_{loc,Rd} = A \cdot f_{loc,d}^{axial}. \tag{4.9}$$

In (4.9) the design value of local critical stress, $f_{loc,d}^{axial}$, can be calculated as:

$$f_{loc,d}^{axial} = \frac{1}{\gamma_f} \cdot \min\{(f_{loc,k}^{axial})_f, (f_{loc,k}^{axial})_w\}, \tag{4.10}$$

where $(f_{loc,k}^{axial})_f$ and $(f_{loc,k}^{axial})_w$ represent, respectively, the critical stress of the uniformly compressed flanges and web, determinable through the expressions reported in Appendix A of this document.
With reference to the symbols in Figure 4-1, the following conservative assumption can be made:

$$\left(f_{loc,k}^{axial}\right)_f = \left(f_{loc,k}^{axial}\right)_f^{SS} = 4 \cdot G_{LT} \cdot \left(\frac{t_f}{b_f}\right)^2, \tag{4.11}$$

corresponding to the critical stress of the flanges simply supported at the connection with the web, $\left(f_{loc,k}^{axial}\right)_f^{SS}$.

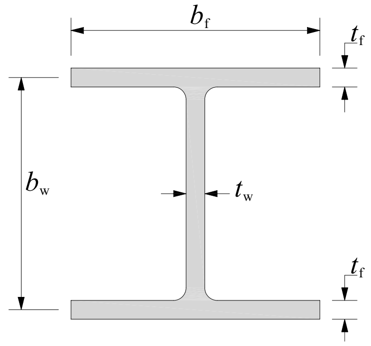


Figure 4-1 – Double symmetric section: symbols used for the geometric dimensions.

The value of the critical stress of the compressed web, $\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{w}}$, can be determined through the following conservative relation:

$$\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{w}} = \left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{w}}^{\mathrm{SS}} = k_{\mathrm{c}} \cdot \frac{\pi^2 \cdot E_{\mathrm{Lc}} \cdot t_{\mathrm{w}}^2}{12 \cdot \left(1 - \nu_{\mathrm{LT}} \cdot \nu_{\mathrm{TL}}\right) \cdot b_{\mathrm{w}}^2}, \tag{4.12}$$

corresponding to the critical stress of the compressed web simply supported at the connection with the flanges, $\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{w}}^{\mathrm{SS}}$.

The coefficient k_{c} in (4.12) is obtained from the relation:

$$k_{\mathrm{c}} = 2 \cdot \sqrt{\frac{E_{\mathrm{Tc}}}{E_{\mathrm{Lc}}}} + 4 \cdot \frac{G_{\mathrm{LT}}}{E_{\mathrm{Lc}}} \cdot \left(1 - \nu_{\mathrm{LT}}^2 \cdot \frac{E_{\mathrm{Tc}}}{E_{\mathrm{Lc}}}\right) + 2 \cdot \nu_{\mathrm{LT}} \cdot \frac{E_{\mathrm{Tc}}}{E_{\mathrm{Lc}}}. \tag{4.13}$$

For the pultrudes classified by UNI EN 13706-3 (Appendix C) the ratio $E_{\mathrm{Tc}}/E_{\mathrm{Lc}}$ results equal to approximately 0.30. For pultrudes currently available in commerce, the following limitations result: $0.12 \le G_{\mathrm{LT}}/E_{\mathrm{Lc}} \le 0.17$ and $0.23 \le \nu_{\mathrm{LT}} \le 0.35$. For these value intervals the (4.13) supplies the minimum value $k_{\mathrm{c}} = 1.70$.

The coefficient χ in (4.8) represents a reductive factor which takes into consideration the interaction between the local and global instability of the element. This coefficient assumes a unitary value either due to slenderness which tends to zero or to the presence of constraints which does not allow global instability, and can be obtained through the expression:

$$\chi = \frac{1}{c \cdot \lambda^2} \cdot \left(\Phi - \sqrt{\Phi^2 - c \cdot \lambda^2}\right). \tag{4.14}$$

The symbols introduced in (4.14) have the following meaning:

- the symbol c represents a numeric coefficient which, in the absence of more accurate tests, can be assumed as equal to 0.65;

- $\Phi = \dfrac{1 + \lambda^2}{2}$.

In the above relation slenderness λ is equal to:

$$\lambda = \sqrt{\frac{N_{\mathrm{loc,Rd}}}{N_{\mathrm{Eul}}}}, \tag{4.15}$$

where $N_{\mathrm{Eul}} = \dfrac{1}{\gamma_{\mathrm{f}}} \cdot \dfrac{\pi^2 \cdot E_{\mathrm{eff}} \cdot J_{\mathrm{min}}}{L_0^2}$ and L_0 is the buckling length of the member.

The function χ, which depends on λ, is plotted in Figure 4-2.

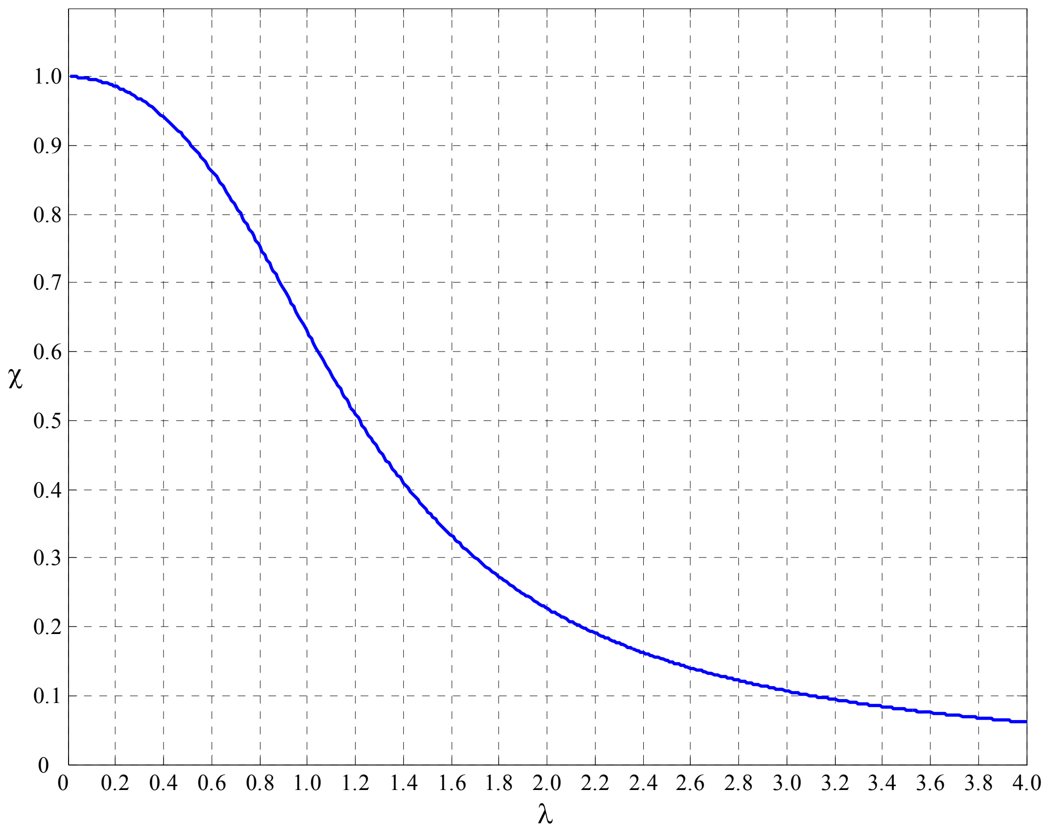


Figure 4-2 – Interaction curve between local and global modes of instability due to axial compression.

4.2 FLEXURE

4.2.1 In-plane flexure

(1) The structures subjected to in-plane flexure should undergo both resistance and stability verification. In the first case, in each transversal section, the design value of the bending moment, M_{Sd}, should satisfy the limitation:

$$M_{\mathrm{Sd}} \leq M_{\mathrm{Rd1}}\,. \tag{4.16}$$

In (4.16) the design value of the flexural resistance of the pultruded element, M_{Rd1}, is obtained from:

$$M_{\mathrm{Rd1}} = \min\left\{W \cdot f_{\mathrm{t,d}},\, W \cdot f_{\mathrm{c,d}}\right\}, \tag{4.17}$$

where W is the modulus of resistance of the section.

(2) In the case of beams under flexure on a symmetrical plane, subjected to a constant bending moment, the verification of stability requires the satisfaction of the following limitation:

$$M_{\mathrm{Sd}} \le M_{\mathrm{Rd2}}, \tag{4.18}$$

where the design value of the bending moment which provokes the instability of the element, M_{Rd2}, can be determined either through tests (§ 3.8 (4)) or numerical/analytical modelling (§ 3.8 (5)).
In the latter case, the analysis can be carried out by attributing the pultruded element an initial imperfection. This imperfection can consist of a field of displacements proportional to the first critical mode, amplified according to the tolerance declared by the manufacturer and not less than that indicated in Appendix B of UNI EN 13706-2.

(3) In the case of beams subjected to a variable bending moment along the axis, apart from a more rigorous evaluation, the verification of stability can be carried out assuming, in place of the stress moment, M_{Sd}, the equivalent moment:

$$M_{\mathrm{eq}} = 1.3\ M_{\mathrm{m}}, \quad \text{with} \quad 0.75\ M_{\max} \le M_{\mathrm{eq}} \le 1.0\ M_{\max}, \tag{4.19}$$

where M_{m} is the mean value of M_{Sd} along the axis and $M_{\max}$ its maximum value.
In the case of a shaft constrained at both ends and subject to a variable linear bending moment between the values of the ends M_{a} and M_{b}, the value of M_{eq} can be assumed as:

$$M_{\mathrm{eq}} = 0.6 \cdot M_{\mathrm{a}} - 0.4 \cdot M_{\mathrm{b}}, \quad \text{with} \quad |M_{\mathrm{a}}| \ge |M_{\mathrm{b}}|, \tag{4.20}$$

provided that $M_{\mathrm{eq}} > 0.4 \cdot M_{\mathrm{a}}$.

(4) For pultrudes with a double symmetric section simply supported through flexure-torsional restraints and subjected to a constant bending moment acting on the plane of maximum inertia of the section, the value of M_{Rd2} can be obtained from the relation:

$$M_{\mathrm{Rd2}} = \chi_{\mathrm{FT}} \cdot M_{\mathrm{loc,Rd}}, \tag{4.21}$$

being $M_{\mathrm{loc,Rd}}$ the design value of the bending moment which determines the local instability of the pultruded element, evaluated through tests carried out on large beams (§ 3.8 (4)) or numerical/analytical modelling (§ 3.8 (5)). In alternative, it can be obtained from the following relation:

$$M_{\mathrm{loc,Rd}} = W \cdot f_{\mathrm{loc,d}}^{\mathrm{flex}}. \tag{4.22}$$

In (4.22), the design value of the critical stress for flexure, $f_{\mathrm{loc,d}}^{\mathrm{flex}}$, should be assumed equal to:

$$f_{\mathrm{loc,d}}^{\mathrm{flex}} = \frac{1}{\gamma_{\mathrm{f}}} \cdot \min\{(f_{\mathrm{loc,k}}^{\mathrm{axial}})_{\mathrm{f}}, (f_{\mathrm{loc,k}}^{\mathrm{flex}})_{\mathrm{w}}\}. \tag{4.23}$$

The value of the critical stress of the compressed flange, $(f_{\mathrm{loc,k}}^{\mathrm{axial}})_{\mathrm{f}}$, can be determined through the expressions reported in Appendix A of this document. The value of (4.11) can be assumed for $(f_{\mathrm{loc,k}}^{\mathrm{flex}})_{\mathrm{f}}$, corresponding to the critical stress of the flange subjected to constant compression and simply supported at the connection with the web.
The value of the critical stress of the web, $(f_{\mathrm{loc,k}}^{\mathrm{flex}})_{\mathrm{w}}$, can be determined, as a precaution, through the

conservative relation:

$$\left(f_{\mathrm{loc,k}}^{\mathrm{flex}}\right)_{\mathrm{w}} = \left(f_{\mathrm{loc,k}}^{\mathrm{flex}}\right)_{\mathrm{w}}^{\mathrm{SS}} = k_{\mathrm{f}} \cdot \frac{\pi^2 \cdot E_{\mathrm{Lc}} \cdot t_{\mathrm{w}}^2}{12 \cdot \left(1-\nu_{\mathrm{LT}} \cdot \nu_{\mathrm{TL}}\right) \cdot b_{\mathrm{w}}^2}, \tag{4.24}$$

where $\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{w}}^{\mathrm{SS}}$ corresponds to the critical tension of the web subjected to a linear symmetric distribution and simply supported at the connection with the flanges.
In (4.24) the coefficient k_{f} is calculated as:

$$k_{\mathrm{f}} = 13.9 \cdot \sqrt{\frac{E_{\mathrm{Tc}}}{E_{\mathrm{Lc}}}} + 22.2 \cdot \frac{G_{\mathrm{LT}}}{E_{\mathrm{Lc}}} \cdot \left(1-\nu_{\mathrm{LT}}^2 \cdot \frac{E_{\mathrm{Tc}}}{E_{\mathrm{Lc}}}\right) + 11.1 \cdot \nu_{\mathrm{LT}} \cdot \frac{E_{\mathrm{Tc}}}{E_{\mathrm{Lc}}}. \tag{4.25}$$

For pultrudes classified by UNI EN 13706-3 (see Appendix C), the ratio $E_{\mathrm{Tc}}/E_{\mathrm{Lc}}$ results approximately equal to 0.30. Whereas, for pultrudes currently available in commerce it results $0.12 \le G_{\mathrm{LT}}/E_{\mathrm{Lc}} \le 0.17$ and $0.23 \le \nu_{\mathrm{LT}} \le 0.35$. For these value intervals, (4.25) gives the minimum value $k_{\mathrm{f}} = 11.00$.

In (4.21) χ_{FT} represents a reductive coefficient which takes into consideration the interaction between the local and global instability of a member subjected to flexure. It assumes a unitary value either due to slenderness which tends to zero or to the presence of restraints which does not allow global instability, and can be obtained from the relation:

$$\chi_{\mathrm{FT}} = \frac{1}{c \cdot \lambda_{\mathrm{FT}}^2} \cdot \left(\Phi_{\mathrm{FT}} - \sqrt{\Phi_{\mathrm{FT}}^2 - c \cdot \lambda_{\mathrm{FT}}^2}\right). \tag{4.26}$$

The symbols introduced in (4.26) have the following meaning:

- c is a coefficient which, in the absence of a more accurate evaluation, can be assumed to be equal to 0.70;

- $\Phi_{\mathrm{FT}} = \dfrac{1+\lambda_{\mathrm{FT}}^2}{2}$;

- $\lambda_{\mathrm{FT}} = \sqrt{\dfrac{M_{\mathrm{loc,Rd}}}{M_{\mathrm{FT}}}}$.

In the definition of the parameter of slenderness, λ_{FT}, reported above, the critical moment due to flexure-torsional instability, M_{FT}, is:

$$M_{\mathrm{FT}} = \frac{1}{\gamma_{\mathrm{f}}} \cdot \frac{\pi^2}{L^2} \cdot E_{\mathrm{eff}} \cdot J_{\mathrm{min}} \cdot \sqrt{\frac{J_{\omega}}{J_{\mathrm{min}}} \cdot \left(1 + \frac{G_{\mathrm{eff}} \cdot J_{\mathrm{t}}}{E_{\mathrm{eff}} \cdot J_{\omega}} \cdot \frac{L^2}{\pi^2}\right)}, \tag{4.27}$$

where L is the distance between the ends, J_{min} the minimum value of the moment of inertia, J_{t} the torsional stiffness factor and J_{ω} the warping stiffness factor.
The elasticity moduli E_{eff} and G_{eff} can be determined through three point load tests on samples

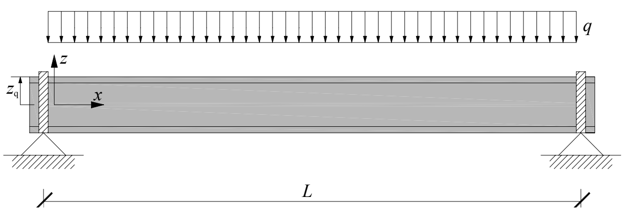
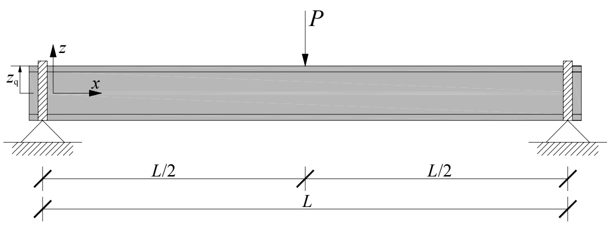
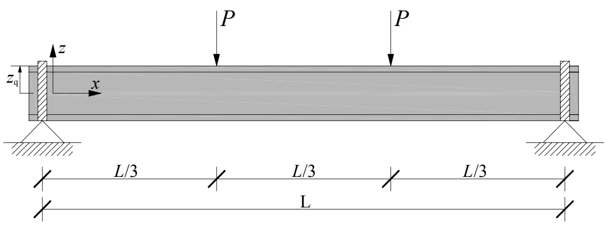
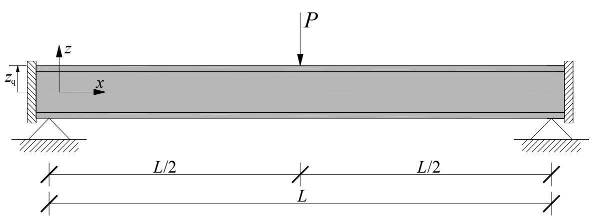
conforming to the indications set out in Appendix D and Appendix G of UNI EN 13706-2, respectively.

(5) In the case of pultrudes with a double symmetric section subjected to a variable bending moment on the plane of maximum inertia, the expression (4.21) of M_{Rd2} can be used to verify the stability if the factor λ_{FT} in (4.26) is evaluated assuming that the critical flexure-torsional moment of instability M_{FT} has the following expression:

$$M_{\mathrm{FT}} = \frac{1}{\gamma_{\mathrm{f}}} \cdot \frac{C_1}{k} \cdot \frac{\pi^2}{L^2} \cdot E_{\mathrm{eff}} \cdot J_{\min} \cdot \left[-C_2 \cdot z_{\mathrm{q}} + \sqrt{\left(\frac{C_2 \cdot z_{\mathrm{q}}}{k} \right)^2 + \frac{J_\omega}{J_{\min}} \cdot \left(\frac{1}{k^2} + \frac{G_{\mathrm{eff}} \cdot J_{\mathrm{t}}}{E_{\mathrm{eff}} \cdot J_\omega} \cdot \frac{L^2}{\pi^2} \right)} \right], \tag{4.28}$$

where L is the distance between two consecutive flexure-torsional restraints and z_{q} is the coordinate of the load application point in relation to the centroid of the profile. The values of the coefficients C_1, C_2 and k are reported in Table 4-1 for several cases of load and constraint.

Table 4-1 – Coefficients C_1, C_2 and k for several conditions of restraint and load (φ_x, φ_z rotations around the axes x and z; ψ twisting rotation).

Constraint conditions of the ends and load (on the plane)	φ_x	φ_z	ψ	C1	C2	k
	F(*)	F	F	1.13	0.45	1.00
	F	F	F	1.35	0.55	1.00
	F	F	F	1.12	0.51	1.00
	F	R(**)	R	1.07	0.42	0.50

(*) F= free, (**) R = restrained

(6) In order to verify the local instability of the flanges of double symmetric pultrudes simply supported under flexure within the plane of minimum inertia, the design value of the critical bending moment can be evaluated either through tests (§ 3.8 (4)) or numerical/analytical (§ 3.8 (5)) procedures.
In particular, in the case of a constant bending moment, a 2-D model can be used limiting the study to the flange subjected at the two extremities to a linear symmetrical distribution of normal stresses and constrained at the connection with the web. This constraint could be modelled as a rotational restraint of stiffness $\tilde{k} = \dfrac{E_{\mathrm{Tc}} \cdot t_{\mathrm{w}}^3}{b_{\mathrm{w}} \cdot 12\left(1-\nu_{\mathrm{LT}} \cdot \nu_{\mathrm{TL}}\right)}$, equal to the flexure-stiffness (transversal) of the web.
A further delimitation of the critical load could be obtained assuming that the web represents a simple restraint for the flange ($\tilde{k} = 0$).

4.2.2 In-plane tenso-flexure

(1) In the case of prismatic profile beams subjected to an axial tension load, $N_{\mathrm{Lt,Sd}}$, as well as a constant bending moment, M_{Sd}, on one of the main planes, in every transversal section the following limitation should be satisfied for the ULS:

$$\frac{N_{\mathrm{t,Sd}}}{N_{\mathrm{t,Rd}}} + \frac{M_{\mathrm{Sd}}}{M_{\mathrm{Rd1}}} \leq 1, \tag{4.29}$$

where $N_{\mathrm{t,Rd}}$ is the design tensile resisting force defined in § 4.1.1 and M_{Rd1} is the design resisting moment in the flexure plane, to be calculated through the expression (4.17).

(2) In addition to the aforementioned verification of resistance, stability should also be verified. In the absence of an exact evaluation of the critical load, it is possible to ignore tensile stresses and use the procedure for the case of plane flexure.

4.2.3 In plane compression-flexure

(1) In the case of double symmetrical prismatic beams subjected to an axial compression force, $N_{\mathrm{c,Sd}}$, as well as a constant bending moment, M_{Sd}, acting on the plane of maximum inertia, in every transversal section the verification of resistance should be satisfied for the ULS:

$$\frac{N_{\mathrm{c,Sd}}}{N_{\mathrm{c,Rd1}}} + \frac{M_{\mathrm{Sd}}}{M_{\mathrm{Rd1}}} \leq 1, \tag{4.30}$$

where $N_{\mathrm{c,Rd1}}$ is the design compressive resisting force defined by (4.7) and M_{Rd1} is the design resisting moment, to be calculated with the expression (4.17).

(2) In addition to the aforementioned verification of resistance, stability should also be verified. In the absence of an exact evaluation of the critical load, this verification can be carried out through the following limitation:

$$\frac{N_{\mathrm{c,Sd}}}{N_{\mathrm{c,Rd2}}} + \frac{M_{\mathrm{Sd}}}{M_{\mathrm{Rd2}} \cdot \left(1 - \dfrac{N_{\mathrm{c,Sd}}}{N_{\mathrm{Eul}}}\right)} \leq 1. \tag{4.31}$$

The symbols introduced in (4.31) have the following meaning:

- $N_{c,Rd2}$ represents the design value of the compressive force which provokes the instability of the element which, in the case of double T sections, can be obtained from (4.8);

- M_{Rd2} represents the design value of the bending moment which provokes flexural instability which, in the case of double T profiles, can be evaluated conforming to (4.21);

- N_{Eul} represents the value of the Eulerian critical load.

The value of the Eulerian critical load, N_{Eul}, introduced in (4.31), is given by the following expression:

$$N_{Eul} = \frac{1}{\gamma_f} \cdot \frac{\pi^2 \cdot E_{eff} \cdot J}{L_0^2}, \tag{4.32}$$

where L_0 and J are the buckling length of inflection and the moment of inertia on the flexural plane, respectively.

(3) In the presence of a variable bending moment, the equivalent moment, M_{eq}, can be assumed rather than the stressing moment, M_{Sd}, determined as described in (3) of § 4.2.1.

(4) For pultrudes with double T section subjected to a variable bending moment, the value of the bending moment which provokes the flexure-torsional instability, M_{FT}, can be calculated through the expression (4.28).

4.3 SHEAR

4.3.1 Shear resistance

(1) The design value of shear, V_{Sd}, for each transversal section, should satisfy the limitation:

$$V_{Sd} \leq V_{Rd}. \tag{4.33}$$

In (4.33) the design resisting shear force, V_{Rd}, is obtained from:

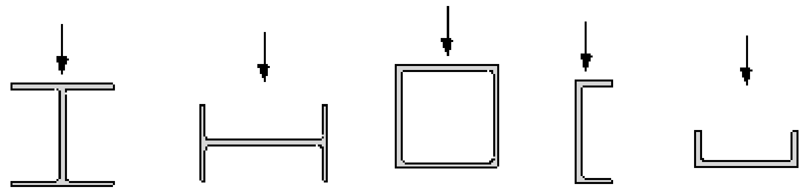
$$V_{Rd} = \min\{V_{Rd1}, V_{Rd2}\}. \tag{4.34}$$

The quantity V_{Rd1} can be obtained using the relation:

$$V_{Rd1} = A_V \cdot f_{V,Rd}, \tag{4.35}$$

where $f_{V,Rd}$ is the design shear resistance of the material and A_V the area of the section resistant to shear given in Table 4-2 for the most widely used pultrudes.

Table 4-2 – Area resistant to shear A_v for several thin pultrudes.

(a)	(b)	(c)	(d)	(e)
				
$b_w \cdot t_w$	$(2b_f \cdot t_f)/1.2$	$2b_w \cdot t_w$	$b_w \cdot t_w$	$(2b_f \cdot t_f)/1.2$

The design shear value which provokes the local instability of the element, V_{Rd2}, can be determined either through tests (§ 3.8 (4)) or numerical/analytical modelling (§ 3.8 (5)).
In the case of pultrudes with a plane section as reported in Table 4-2 (a, c, d), the value of V_{Rd2} can be determined through the expression:

$$V_{Rd2} = V_{loc,Rd} = \frac{1}{\gamma_f} \cdot A_V \cdot f_{V,loc,k} \,. \tag{4.36}$$

In (4.36), $f_{V,loc,k}$ is the characteristic value of stress which determines the local instability of the panel of the web, assumed to be simply supported at the connection with flanges. This value can be determined as:

$$f_{V,loc,k} = \frac{4}{t_w \cdot b_w^2} \cdot \left(8.125 + 5.045 \cdot K\right) \cdot \sqrt[4]{\left(D_{11}\right)_w \cdot \left(D_{22}\right)_w^3}, \quad \text{for } K \le 1\,, \tag{4.37}$$

$$f_{V,loc,k} = \frac{4}{t_w \cdot b_w^2} \cdot \left(11.71 + \frac{1.46}{K^2}\right) \cdot \sqrt{\left(D_{22}\right)_w \cdot \left[\left(D_{12}\right)_w + 2 \cdot \left(D_{66}\right)_w\right]}, \quad \text{for } K > 1\,. \tag{4.38}$$

In (4.37) and (4.38), K assumes the form:

$$K = \frac{\dfrac{G_{LT}}{6} + \nu_{LT} \cdot \dfrac{E_{Tc}}{12 \cdot \left(1 - \nu_{LT} \cdot \nu_{TL}\right)}}{\sqrt{\dfrac{E_{Lc} \cdot E_{Tc}}{\left[12 \cdot \left(1 - \nu_{LT} \cdot \nu_{TL}\right)\right]^2}}}\,. \tag{4.39}$$

(2) Local verifications should be done on sections where concentrated loads are applied. In particular, it should be controlled that:

$$f_{Sd,z} \le f_{Tc,Rd}\,, \tag{4.40}$$

where $f_{Sd,z}$ is the design value of compressive stress acting in transversal direction.
In order to avoid local instability phenomena appropriate stiffening systems can be applied to the plane sections.

4.4 TORSION

4.4.1 Torsion resistance

(1) The analysis of the elements with double T transversal section subjected to torsion should be carried out in reference to an appropriate model capable of supplying both the primary twisting contribution, $T_{\mathrm{Sd}}^{\mathrm{SV}}$, as well as the secondary twisting contribution, T_{Sd}^{ω}.

The verification of the section results satisfied when the following relation is fulfilled:

$$t_{\mathrm{f}} \cdot \frac{T_{\mathrm{Sd}}^{\mathrm{SV}}}{J_{\mathrm{t}}} + 1.5 \cdot \frac{T_{\mathrm{Sd}}^{\omega}}{t_{\mathrm{f}} \cdot b_{\mathrm{f}} \cdot b_{\mathrm{w}}} \leq f_{\mathrm{V,Rd}} . \tag{4.41}$$

(2) The verification of pultruded profiles with L or T cross-sections should satisfy the limitation:

$$t_{\max} \cdot \frac{T_{\mathrm{Sd}}^{\mathrm{SV}}}{J_{\mathrm{t}}} \leq f_{\mathrm{V,Rd}} . \tag{4.42}$$

(3) It is possible not to take into account the term T_{Sd}^{ω} when verifying boxed shapes.

4.5 FLEXURE AND SHEAR

4.5.1 Flexure and shear resistance

(1) The verification of the panels of the web of pultrudes subjected to flexure on the plane, M_{Sd}, and shear, V_{Sd}, should be carried out respecting the following limitation:

$$\left(\frac{M_{\mathrm{Sd}}}{M_{\mathrm{Rd}}}\right)^2 + \left(\frac{V_{\mathrm{Sd}}}{V_{\mathrm{Rd}}}\right)^2 \leq 1 , \tag{4.43}$$

where V_{Rd} is defined in (4.34) and M_{Rd} corresponds to the minimum between M_{Rd1} and M_{Rd2}.

5 VERIFICATION OF THE ULTIMATE LIMIT STATES OF THE JOINTS

The joints between the structural elements can be either bolted, riveted or bonded as well as a combination of the three.

5.1 STRESSES

(1) The stresses acting on the joints should be determined through an elastic analysis of the structure or appropriate substructure.

5.2 JOINT RESISTANCE

(1) All the joints should have an adequate design resistance to the actions which could influence the structure during its service life.

(2) Joint resistance should be evaluated taking into account the resistance of each single joint element.

(3) Verification of the joint resistance should be carried out taking into account all the possible failure modes of the connected parts.

(4) Verification of resistance should take into account the orientation of the stresses in order to determine the resistant stresses.

5.3 DESIGN CRITERIA

(1) The joints should be designed in relation to the following conditions:

- the internal forces and moments should be in equilibrium with the applied forces and moments;
- each element of the joint should be capable of resisting the considered forces.

(2) In the case of bolted joints, the forces on every single bolt can not be evaluated with simple equilibrium criteria, as in the case of ductile materials.

(3) In general, bolted joints should be designed so that the axes of the structural elements converge in the same point.

(4) In the case of joints which are not assimilated into nodes, the eccentricity of the forces should be taken into account when evaluating the forces.

5.4 BOLTED JOINTS

5.4.1 General

(1) The proposed bolted joints are realised from stainless steel bolts. Particular attention should be given when using FRP bolts, especially in relation to their deformability.

(2) In the case of bolted joints subjected to shear, the bolts should have all the same diameter and at least two of them should go in the load direction.
(3) In general, the diameter of the bolts should not be less than the thickness of the thinnest connected elements and no greater than one and half times the same (Table 5-1).

(4) Particular attention should be given when realising the hole. It should have a diameter which allows the bolt to pass through without being forced. In every case, the difference between the diameter of the hole, d, and that of the bolt, d_b, should not exceed 1 mm (Table 5-1).

(5) Rigid washers should be inserted under the bolt head as well as the nut. They should have an external diameter equal to at least twice that of the bolt and a thickness which guarantees a uniform pressure on the surface of the FRP element (Table 5-1).

(6) The joints should be designed taking into account, for each bolt, a tightening torque capable of guaranteeing an adequate diffusion of the stresses around the hole. In verifying the bolts, the effect of this stress diffusion should not be taken into account.

(7) Particular attention should be given to the operations of fastening the bolt, taking into account the stress resistance of the pultrudes in the orthogonal direction of the fibres.

(8) The distances between the centre of the holes, w_x and w_y, should not be less than four times the diameter of the bolts (Figure 5-1).

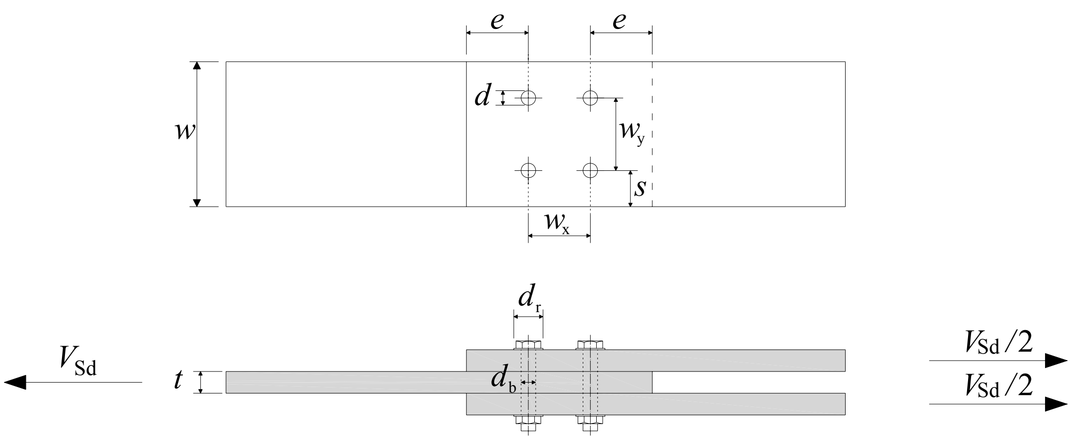


Figure 5-1 – Bolted Joint.

(9) In the shear verification, bolt-shear failure in the direction of the fibres should be avoided. An appropriate ratio e/d_b between the distance of the bolt from the edge of the element in the direction of the stress, e, and the diameter of the bolt, d_b, should be taken into account (Figure 5-1).

(10) The ratio between the distance of the bolt from the edge in the orthogonal direction of the strain, s, and the diameter of the bolt, d_b, should not be less than half of the ratio between the transversal distance between two consecutive holes, w_y, and the diameter of the bolt (Table 5-1).

Table 5-1 – Geometric limitations relative to a bolted joint.

Bolt diameter (recommended)	$t_{min} \le d_b \le 1.5 \cdot t_{min}$ $d_b \ge t_{min}$
Hole diameter	$d \le d_b + 1$ mm
Washer diameter	$d_r \ge 2 \cdot d_b$
Distances between holes	$w_x \ge 4 \cdot d_b$ $w_y \ge 4 \cdot d_b$
Distances from edges	$e/d_b \ge 4$ $s/d_b \ge 1/2 \cdot (w_y/d_b)$

5.4.2 Design criteria

(1) The equilibrium conditions should always be satisfied in the determination of:

- the division of the force among the bolts;
- the distribution of the stresses near the holes;
- the distribution of the stresses distant from the holes.

(2) The verification of joint resistance should be carried out taking into account the eventual simultaneous presence of more than one stress-tensor components.

(3) In the verification of bolted joints subjected to shear, the following failure modes should be taken into account:

- net-section failure;
- bolt-shear failure;
- bearing failure;
- shear-out failure.

(4) In the case of bolts subjected to traction strains, the following failure modes should be taken into account:

- pull-out failure of the FRP element;
- bolt failure due to traction.

(5) The verification of bolted joints subjected to shear and traction should be carried out assuming a conservative linear failure criterium. Different failure criteria can be used in the case of designing aided by either experimental tests results (§ 3.8 (4)) or numerical/analytical modelling (§ 3.8 (5)).

5.4.3 Verification of bolted joints subjected to shear

(1) In the case in which the resultant of the applied external forces passes through the centre *G*

of the bolted connection (Figure 5-2), the coefficients reported in Table 5-2 can be assigned to the bolts.
For joints between FRP elements and metallic elements, the first row of bolts is the nearest to the end of the FRP element.

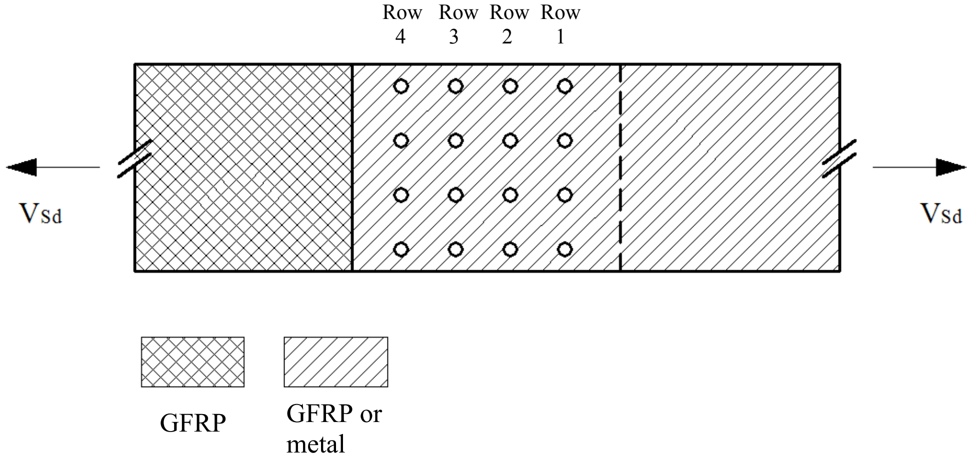


Figure 5-2 – Lay out of the rows of holes in a bolting between two FRP elements or one FRP and one of metal. The resultant of the external forces, V_{Sd}, passes through the centre of the bolted connection.

Table 5-2 – Verification of bolted joints: distribution coefficients of the shear force for each row of bolts.

Number of rows		row 1	row 2	row 3	row 4
1	FRP/FRP	120 %			
	FRP/metal	120 %			
2	FRP/FRP	60 %	60 %		
	FRP/metal	70 %	50 %		
3	FRP/FRP	60 %	25 %	60 %	
	FRP/metal	60 %	30 %	30 %	
4	FRP/FRP	40 %	30 %	30 %	40 %
	FRP/metal	50 %	35 %	25 %	15 %
> 4	Not recommended				

5.4.3.1 Verification of net-section failure

(1) The verification of normal stresses of the resistant section of the element weakened by the presence of the holes should be carried out in relation to the following limitations:

- traction force parallel to the fibre direction (Figure 5-3a):

$$V_{Sd} \leq \frac{1}{\gamma_{Rd}} \cdot f_{Lt,Rd} \cdot \left(w - n \cdot d\right) \cdot t\,, \tag{5.1}$$

- traction force orthogonal to the fibre direction (Figure 5-3b):

$$V_{\mathrm{Sd}} \leq \frac{1}{\gamma_{\mathrm{Rd}}} \cdot f_{\mathrm{Tt,Rd}} \cdot (w - n \cdot d) \cdot t\,, \tag{5.2}$$

where γ_{Rd} is the partial model coefficient, for perforated sections (§ 4.1.1) assumed to be equal to 1.11, V_{Sd} is the force transmitted by the bolt to the element, $f_{\mathrm{Lt,Rd}}$ and $f_{\mathrm{Tt,Rd}}$ are the design traction resistances of the material along the fibre direction and orthogonal to the fibre direction, respectively, t is the thickness of the FRP element and n is the number of holes.
In the case of mono-axial strengthening, if the force V_{Sd} is inclined with a generic angle α in relation to the fibre direction, $f_{\alpha\mathrm{t,Rd}} = f_{\mathrm{Tt,Rd}}$ due to $\alpha > 6°$ being assumed.

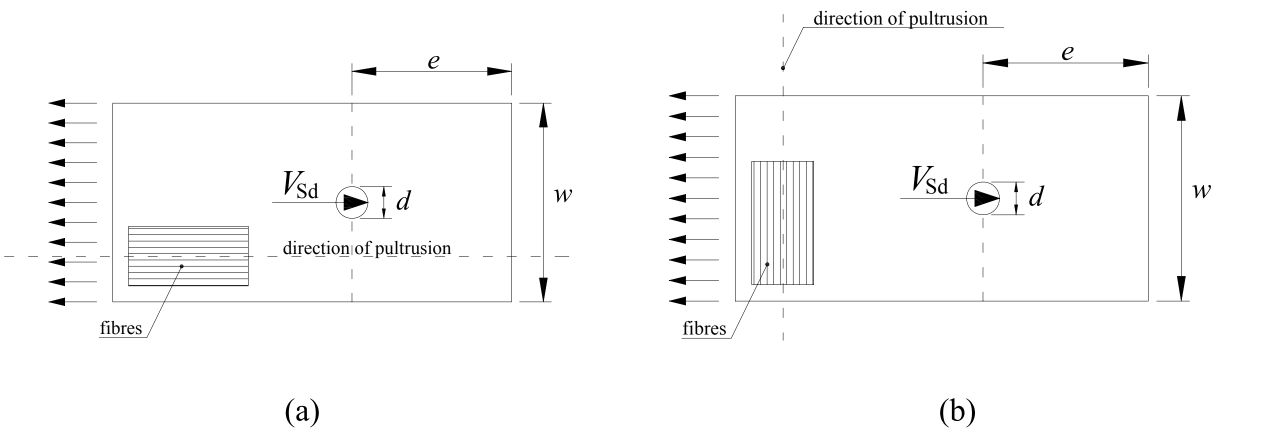


Figure 5-3 – Net-section failure mechanism.

5.4.3.2 Verification of bolt-shear failure

(1) Verification of bolt-shear failure (Figure 5-4) should be carried out following::

$$V_{\mathrm{Sd}} \leq f_{\mathrm{V,Rd}} \cdot (2\,e - d) \cdot t\,, \tag{5.3}$$

being $f_{\mathrm{V,Rd}}$ the design shear resistance of the FRP element.

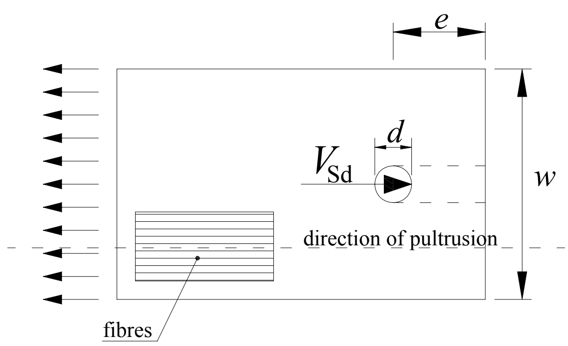


Figure 5-4 – Bolt-shear failure mechanism.

5.4.3.3 Verification of bearing failure

(1) In verifying bearing failure, the mean value of the pressure on the shank of the bolt on the

surface of the hole should satisfy the following limitations:

- force parallel to the fibre direction (Figure 5-5a):

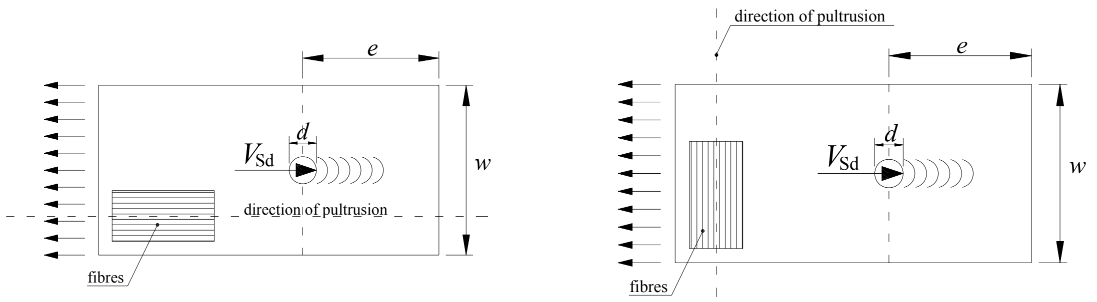
$$V_{\mathrm{Sd}} \leq f_{\mathrm{Lr,Rd}} \cdot d_{\mathrm{b}} \cdot t\,, \tag{5.4}$$

- force orthogonal to fibre direction (Figure 5-5b):

$$V_{\mathrm{Sd}} \leq f_{\mathrm{Tr,Rd}} \cdot d_{\mathrm{b}} \cdot t\,, \tag{5.5}$$

where $f_{\mathrm{Lr,Rd}}$ and $f_{\mathrm{Tr,Rd}}$, are the design resistance to bearing failure of the material in the fibre direction and orthogonal to the fibre direction, respectively.

(2) In order to attribute a pseudo-ductile behaviour to the failure mechanism, a confinement action within the material must be exercised by the washer and the fastening of the bolt should be guaranteed.



(a) (b)

Figure 5-5 – Bearing failure.

5.4.3.4 Verification of shear failure of a steel bolt

(1) In the verification of shear failure of a steel bolt, the following limitation should be satisfied:

$$V_{\mathrm{Sd}} \leq f_{\mathrm{Vb,Rd}} \cdot A_{\mathrm{b}}\,, \tag{5.6}$$

where $f_{\mathrm{Vb,Rd}}$ represents the shear design resistance of the bolt, as defined by the currently adopted regulations and A_{b} is the resistant area of the section of the bolt.

5.4.4 Verification of bolted joints subjected to strain

5.4.4.1 Verification of pull-out failure

(1) Pull-out failure occurs with the perforation of the FRP element. In reference to Figure 5-6, it should be verified that the following results:

$$N_{\mathrm{Sd}} \leq f_{\mathrm{V,Rd}} \cdot \pi \cdot d_{\mathrm{r}} \cdot t\,, \tag{5.7}$$

where d_r is the diameter of the washer.

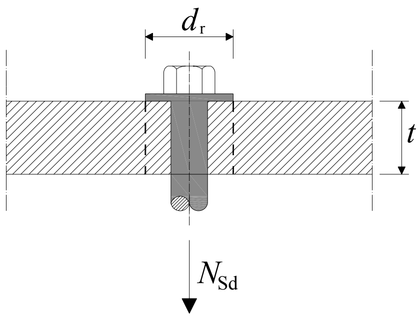


Figure 5-6 – Pull-out failure mechanism.

5.4.4.2 Verification of tension failure of a steel bolt

(1) Verification of steel bolt under tensile force should be carried out according to the following limitation:

$$N_{Sd} \leq F_{tb,Rd}\,, \tag{5.8}$$

where $F_{tb,Rd}$ is the design strain resistance of the bolt, as defined in the currently adopted rules.

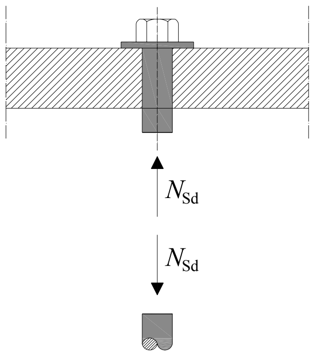


Figure 5-7 – Bolt failure due to strain.

5.5 BONDED JOINTS

5.5.1 General

(1) The bonded joints taken into account in this document are made from FRP elements (adherents) subjected to axial force. The most common configurations are illustrated in Figure 5-8.

(2) The mechanical behaviour of joints c) and d) can be reduced to joints a) and b), respectively.
On the basis of the large number of studies available in current literature, in the case a) the use of two adherents with the same thickness is recommended (simple-lap symmetrical joint).

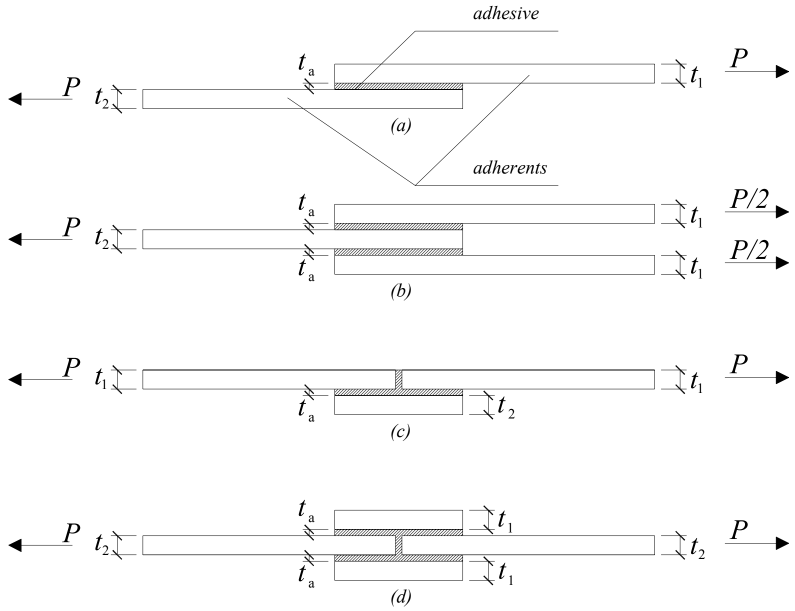


Figure 5-8 – Types of bonded joints: a) simple-lap; b) weighted double-lap; c) simple covered-joint; d) double covered-joint.

5.5.2 Constitutive laws of the interface

(1)P The layer of adhesive contrasts the relative displacements between the bonded elements (Figure 5-9): the transversal displacements, δ, which induce an opening between the adherents, and those in the longitudinal direction, s, which induce sliding.

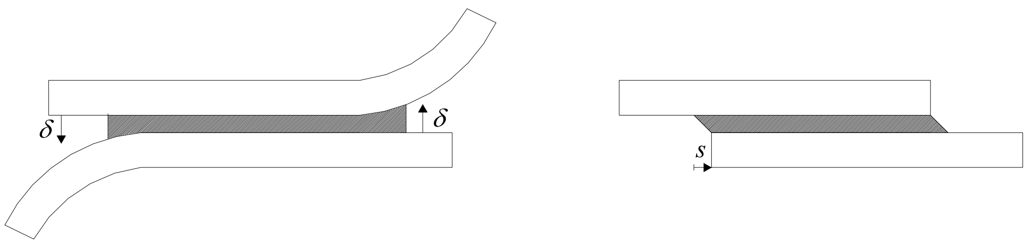


Figure 5-9 – Relative displacements between the adherents.

(2)P By denoting σ and τ, respectively, the normal interfacial stress (orthogonal to plane of the joint) and the shear stress (parallel to the plane of the joint, along the direction of the axes of the joint) can be defined two uncoupled design cohesive laws, $\sigma(\delta)$ and $\tau(s)$ (Figure 5-10).
The displacement at the end of the linear range in both diagrams is generally much less than at the end of the *"softening"* range.
The subtended areas of the two diagrams are equal to the fracture energies for mode I (diagram $\sigma(\delta)$) and mode II (diagram $\tau(s)$), respectively.

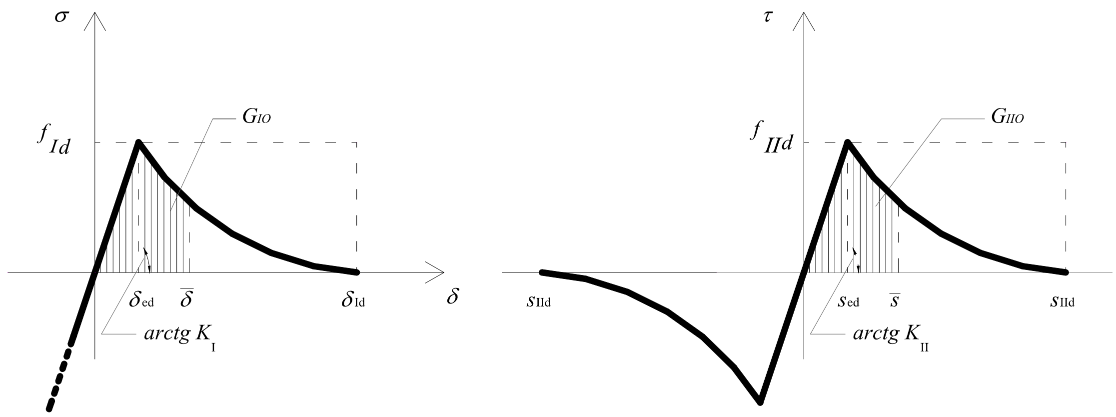


Figure 5-10 – Cohesive interfacial laws.

(3) Apart from more rigorous evaluations, the constitutive interface laws can be generally simplified by assimilating the mechanical behaviour of the adhesive to that of two continual series of independent springs (Figure 5-11), with the first one contrasting the relative displacements δ, while the other one the relative displacements s. Thus adopting the constitutive laws represented by the diagrams in Figure 5-12 in terms of design values. These diagrams subtend areas equal to those represented by the diagrams in Figure 5-10.

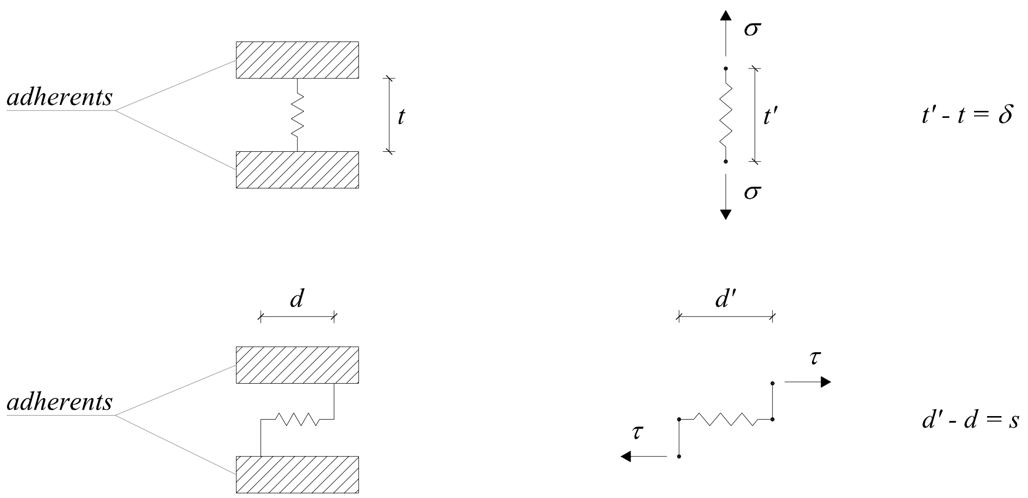


Figure 5-11 – Transversal and longitudinal springs.

The simplified interface laws, in terms of design values, are presented in Figure 5-12.

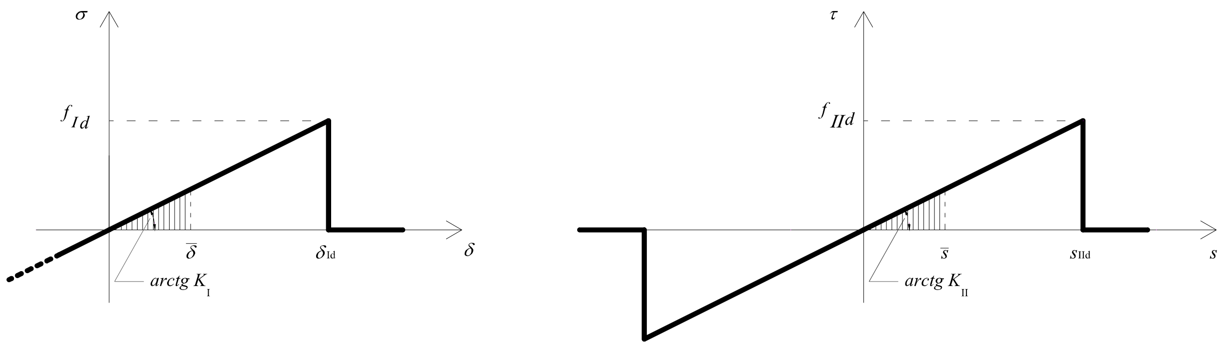


Figure 5-12 – Simplified interface laws.

The first set of springs exercises a normal stress on the interface, which referred to the unit of the surface is:

$$\sigma = k_{\mathrm{I}} \cdot \delta \quad \text{if } \delta \le \delta_{\mathrm{Id}}, \tag{5.9a}$$

$$\sigma = 0 \quad \text{if } \delta > \delta_{\mathrm{Id}}, \tag{5.9b}$$

in which:

$$k_{\mathrm{I}} = \frac{f_{\mathrm{Id}}}{\delta_{\mathrm{Id}}}. \tag{5.9c}$$

Analogously, the second set of springs exercises a tangential stress, along the axis of the joint, which referred to the unit of the surface is:

$$\tau = k_{\mathrm{II}} \cdot s \quad \text{if } |s| \le s_{\mathrm{IId}}, \tag{5.10a}$$

$$\tau = 0 \quad \text{if } |s| > s_{\mathrm{IId}}, \tag{5.10b}$$

in which:

$$k_{\mathrm{II}} = \frac{f_{\mathrm{IId}}}{s_{\mathrm{IId}}}. \tag{5.10c}$$

5.5.3 Interface failure

5.5.3.1 Failure due to debonding of the joint

(1)P If the adherents are subjected to external axial forces and the effects of flexure due to the eccentricity of the interfacial tangential stresses from the axis of the adherents can be assumed not relevant, as is the case with the usual forms of single-lap symmetrical joints as well as double-lap joints, ultimate conditions are achieved according to mode II of failure (*sliding*). In this case, the interface can be designed with springs contrasting the relative axial displacements, the second type indicated in (5.10).

At the ultimate limit state, the joint resistance, N_{Rd}, is that which provokes the displacement s_{IId} within the most elongated spring.

5.5.3.2 Failure due to debonding and opening of the joint

(1)P If the joint is also subjected to shear and flexure, mixed mode I/II of failure occurs and the performance to transfer axial forces is penalised.

(2)P The coupling between the normal and tangential stresses arising at the interface should be taken into account.

(3) In the case of single-lap symmetrical and double-lap joints, the aforementioned effects can be ignored. Consequently, in presence of shear and flexure, it is possible to model the adhesive through springs capable of contrasting the relative transversal displacements between the adherents. Whereas, in presence of axial load, it can be modelled by springs capable of contrasting the relative axial displacements of the adherents.

(4) The value of axial resistance, N^*_{Rd}, can be calculated adopting a suitable mixed mode I/II of fracture, among those presented in current literature. These include the following which can be easily applied due to its additive character:

$$\frac{G_{I}}{G_{IO}} + \frac{G_{II}}{G_{IIO}} = 1 . \tag{5.11}$$

In (5.11) the quantities G_I and G_{II} are, respectively, the areas subtended by the curves of Figure 5-11 or 5-12 over the ranges $\left[0, \overline{\delta}\right]$ and $\left[0, \overline{s}\right]$, where $\overline{\delta}$ and $\overline{s}$ are, in order, the relative transversal and axial displacements related with the design values for the shear/flexure equilibrium problem, and for the extensional one; G_{IO} and G_{IIO} are, respectively, the fracture energy for mode I: $G_{IO} = G_I\left(\overline{\delta} = \delta_{Id}\right)$, and for mode II: $G_{IIO} = G_{II}\left(\overline{s} = s_{IId}\right)$.

5.5.4 Ultimate limit state of the joint

(1) The verification of the ULS of a bonded joint requires that the following limitations are satisfied:

- within the *adherent*: the principal stresses associated to the stresses σ and τ transferred to the interface should result less than the design resistance to traction and compression of the FRP matrix;

- in the *adhesive*:

$$N_{Sd} \leq N_{Rd} , \tag{5.12}$$

where N_{Sd} is the design normal strain which the joint should transfer and N_{Rd} the design normal strain resistance, eventually penalised in order to take into account the presence of shear and flexure stresses.

(2) In the case of joints of FRP adherents, perfectly realised, collapse is generally due to

failure of the base material.

(3) In alternative to what has been previously stated, the resistance of a bonded joint can be verified through appropriate tests (*design by testing*). These can represent a valid tool in the case of joints with particularly complex geometries. The design resistance can be determined in accordance to the procedure indicated in UNI EN 1990.

5.5.5 Practical design regulations

(1) The thickness of the adhesive layer, t_a, should not be less than 0.1 mm.

(2) As a rule, the length of the bonding should not be less than:

$$L^* = \sqrt{\frac{\pi^2 \cdot t_{max} \cdot E_{f\,max}}{k_{II}}}\,, \tag{5.13}$$

where t_{max} and E_{fmax} are, respectively, the larger among the thicknesses of the adherents and the relative longitudinal elasticity moduli.
In the case of shorter lap lengths, more accurate evaluations of the interface resistance are recommended, based on the constitutive interface laws presented in Figure 5-10.

5.5.6 Bonding control

(1) Bonding control should be carried out through either destructive and/or nondestructive tests.

5.5.6.1 Destructive tests

(1) In the case of joints realised either in a factory or on site, samples should be obtained and tested. At least 3 samples of each type of joint should be tested.

5.5.6.2 Nondestructive tests

(1) The nondestructive tests can be used to characterise the homogeneity of the quality of the bonding, with the aim of highlighting any defects including delamination, debonding as well as the presence of empty spaces. Tests include sonic and/or ultra-sonic tests, acoustic as well as thermographic emissions.

6 VERIFICATION OF THE SERVICEABILITY LIMIT STATES

6.1 STRESS VERIFICATION

(1) It should be verified that the stress, f_{Sd}, does not exceed the limit value, f_{Rd}, defined as:

$$f_{\mathrm{Rd}} = \eta \cdot \frac{f_{\mathrm{Rk}}}{\gamma_{\mathrm{f}}}, \tag{6.1}$$

where η is the conversion factor (Table 3-3), f_{Rk} the characteristic value of the corresponding stress element, γ_{f} the safety coefficient of the material.

6.2 STRAIN VERIFICATION

(1)P For a profile under flexure, the value of the deflection should be determined taking into account both the contribution of the flexure deformability as well as the shear deformability.

(2) The recommended values of the vertical displacements are presented in Table 6-1. In order to take into account the viscous behaviour, the evaluation of the displacements for the quasi-permanent load conditions should be carried out assuming reduced values of the corresponding elasticity moduli at the end of the service life of the structure (see point 4).

(3) Values different to those recommended in this Document can be assumed in reference to the protection of non-structural elements.

Table 6-1 – Recommended deflection values.

Quasi-permanent load conditions	$\boldsymbol{\delta_{\mathrm{max}}}$
Plastered storeys, rigid separated walls and any other fragile materials	L/500
Storeys not included in the previous set	L/250
Rare load conditions	$\boldsymbol{\delta_{\mathrm{max}}}$
Pedestrian bridges and any other structures with elevated ratio between accidental and permanent loads	L/100

(4) In the absence of specific test data, the values of the longitudinal and transversal elasticity moduli to time t, following an applied load to time t=0, can be assumed, respectively, equal to:

$$E_{\mathrm{L}}(t) = \frac{E_{\mathrm{L}}}{1+\phi_{\mathrm{E}}(t)}, \tag{6.2}$$

$$G_{\mathrm{LT}}(t) = \frac{G_{\mathrm{LT}}}{1+\phi_{\mathrm{G}}(t)}, \tag{6.3}$$

where the values of the coefficients of viscosity due to longitudinal deformations, $\phi_{\mathrm{E}}(t)$, and shear deformations, $\phi_{\mathrm{G}}(t)$, can be obtained from the FRP manufacturer. In alternative, the values reported in Table 6-2 can be used for these coefficients.

Table 6-2 – Coefficients of viscosity due to longitudinal and shear deformations, at different times elapsed from the load application.

t (elapsed time)	$\phi_E(t)$	$\phi_G(t)$
1 year	0.26	0.57
5 years	0.42	0.98
10 years	0.50	1.23
30 years	0.60	1.76
50 years	0.66	2.09

(5) Viscous effects depend on the temperature of the environment. Appropriate values of the elasticity moduli should be assumed in reference to the environmental conditions in which indicative temperatures of over 50°C can be reached.

7 APPENDIX A

7.1 ON THE LOCAL INSTABILITY OF MEMBERS IN COMPRESSION

(1) As reported in § 4.1.2 (2), in the case of double T elements in compression (Figure 7-1), the design value of the compressive strength which provokes local instability, $N_{\mathrm{loc,Rd}}$, can be determined through the following relation:

$$N_{\mathrm{loc,Rd}} = A \cdot f_{\mathrm{loc,d}}^{\mathrm{axial}}, \tag{7.1}$$

being

$$f_{\mathrm{loc,d}}^{\mathrm{axial}} = \frac{1}{\gamma_{\mathrm{f}}} \cdot \min\{(f_{\mathrm{loc,k}}^{\mathrm{axial}})_{\mathrm{f}}, (f_{\mathrm{loc,k}}^{\mathrm{axial}})_{\mathrm{w}}\}. \tag{7.2}$$

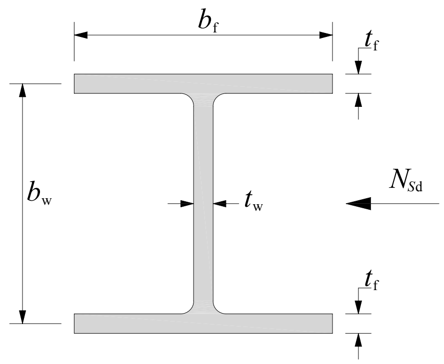


Figure 7-1 – Double T element in compression.

In order to evaluate the critical stress $(f_{\mathrm{loc,k}}^{\mathrm{axial}})_{\mathrm{f}}$, the following expressions (7.3) and (7.4) take into account the stiffness of the rotational constraint exercised by the web on the flanges (Figure 7-2).

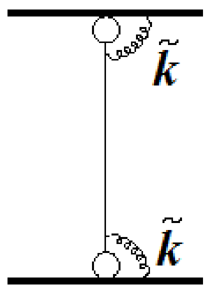


Figure 7-2 – The constraint of the web to the flanges can be represented through rotational springs with stiffness $\tilde{k}$.

$$\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{f}} = \frac{\sqrt{\left(D_{11}\right)_{\mathrm{f}} \cdot \left(D_{22}\right)_{\mathrm{f}}}}{t_{\mathrm{f}}\left(\frac{b_{\mathrm{f}}}{2}\right)^2} \left\{K \cdot \left[15.1 \cdot \eta \cdot \sqrt{1-\rho} + 6 \cdot (1-\rho) \cdot (1-\eta)\right] + \frac{7 \cdot (1-K)}{\sqrt{1+4.12 \cdot \zeta}}\right\}, \text{ for } K \le 1 \tag{7.3}$$

$$\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{f}} = \frac{\sqrt{\left(D_{11}\right)_{\mathrm{f}} \cdot \left(D_{22}\right)_{\mathrm{f}}}}{t_{\mathrm{f}} \cdot \left(\frac{b_{\mathrm{f}}}{2}\right)^2} \cdot \left[15.1 \cdot \eta \cdot \sqrt{1-\rho} + 6 \cdot (1-\rho) \cdot (K-\eta)\right], \text{ for } K > 1 \tag{7.4}$$

Quantities ζ, ρ, η and K introduced in (7.3) and (7.4) have the following expressions:

- $\zeta = \dfrac{(D_{22})_{\mathrm{f}}}{\tilde{k} \cdot \dfrac{b_{\mathrm{f}}}{2}}$;

- $\rho = \dfrac{(D_{12})_{\mathrm{f}}}{2 \cdot (D_{66})_{\mathrm{f}} + (D_{12})_{\mathrm{f}}}$;

- $\eta = \dfrac{1}{\sqrt{1 + (7.22 - 3.55 \cdot \rho) \cdot \zeta}}$;

- $K = \dfrac{2 \cdot \left(D_{66}\right)_{\mathrm{f}} + \left(D_{12}\right)_{\mathrm{f}}}{\sqrt{\left(D_{11}\right)_{\mathrm{f}} \cdot \left(D_{22}\right)_{\mathrm{f}}}}$.

The torsional stiffness given by the web, $\tilde{k}$, (assuming characteristic values of the elasticity moduli) can be represented through the relation:

$$\tilde{k} = \frac{\left(D_{22}\right)_{\mathrm{w}}}{b_{\mathrm{w}}} \cdot \left[1 - \frac{t_{\mathrm{f}} \cdot \left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{f}}^{\mathrm{SS}} \cdot \dfrac{1}{\left(E_{\mathrm{Lc}}\right)_{\mathrm{f}} \cdot t_{\mathrm{f}}}}{t_{\mathrm{w}} \cdot \left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{w}}^{\mathrm{SS}} \cdot \dfrac{1}{\left(E_{\mathrm{Lc}}\right)_{\mathrm{w}} \cdot t_{\mathrm{w}}}}\right]. \tag{7.5}$$

In the expression (7.5), $\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{f}}^{\mathrm{SS}}$ and $\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{w}}^{\mathrm{SS}}$ represent the critical stresses, relative to the flanges and the centre of the pultruded element, respectively, corresponding to $\tilde{k} = 0$. They can be evaluated either as in (4.11) and (4.12) or, alternatively, through the following expressions:

$$\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{f}}^{\mathrm{SS}} = \frac{12 \cdot \left(D_{66}\right)_{\mathrm{f}}}{t_{\mathrm{f}} \cdot \left(\frac{b_{\mathrm{f}}}{2}\right)^2}, \tag{7.6}$$

$$\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{w}}^{\mathrm{SS}}=\frac{\pi^{2}}{t_{\mathrm{w}}\cdot b_{\mathrm{w}}^{2}}\cdot\left\{2\cdot\sqrt{\left(D_{11}\right)_{\mathrm{w}}\cdot\left(D_{22}\right)_{\mathrm{w}}}+2\cdot\left[\left(D_{12}\right)_{\mathrm{w}}+2\cdot\left(D_{66}\right)_{\mathrm{w}}\right]\right\}, \tag{7.7}$$

where the values of flexural stiffness relative to the flanges are obtained from the following relations (assuming characteristic values of the elasticity moduli):

$$D_{11}=\frac{E_{\mathrm{Lc}}\cdot t^{3}}{12\cdot\left(1-\nu_{\mathrm{LT}}\cdot\nu_{\mathrm{TL}}\right)}, \tag{7.8}$$

$$D_{12}=\nu_{\mathrm{LT}}\cdot D_{22}, \tag{7.9}$$

$$D_{22}=\frac{E_{\mathrm{Tc}}\cdot t^{3}}{12\cdot\left(1-\nu_{\mathrm{LT}}\cdot\nu_{\mathrm{TL}}\right)}, \tag{7.10}$$

$$D_{66}=\frac{G_{\mathrm{LT}}\cdot t^{3}}{12}. \tag{7.11}$$

In order to evaluate the critical stress $(f_{\mathrm{loc,k}}^{\mathrm{axial}})_{\mathrm{w}}$, the following expression (7.12) takes into account the torsional stiffness (GJ_{t}) of the constraint given by the edges in relation to the centre of the pultruded element.

$$\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{w}}=\frac{\pi^{2}}{t_{\mathrm{w}}\cdot b_{\mathrm{w}}^{2}}\cdot\left\{2\cdot\sqrt{1+4.139\xi'}\cdot\sqrt{\left(D_{11}\right)_{\mathrm{w}}\cdot\left(D_{22}\right)_{\mathrm{w}}}+\left(2+0.62\cdot\xi'^{2}\right)\cdot\left[\left(D_{12}\right)_{\mathrm{w}}+2\cdot\left(D_{66}\right)_{\mathrm{w}}\right]\right\} \tag{7.12}$$

where:

- $\xi'=\dfrac{1}{1+10\cdot\zeta'}$;

- $\zeta=\dfrac{(D_{22})_{\mathrm{w}}}{\left(GI_{t}\right)\cdot\dfrac{b_{\mathrm{w}}}{2}}$;

- $\left(GI_{\mathrm{t}}\right)=4\cdot\left(D_{66}\right)_{\mathrm{f}}\cdot b_{\mathrm{f}}\cdot\left[\dfrac{1-\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{w}}^{\mathrm{SS}}\cdot\left(\dfrac{1}{E_{\mathrm{Lc}}\cdot t_{\mathrm{w}}}\right)}{\left(f_{\mathrm{loc,k}}^{\mathrm{axial}}\right)_{\mathrm{f}}^{\mathrm{SS}}\cdot\left(\dfrac{1}{E_{\mathrm{Lc}}\cdot t_{\mathrm{f}}}\right)}\right]$.

8 APPENDIX B

8.1 PRODUCTION TECHNIQUES OF FRP PULTRUDES

(1) The main production process of FRP structural elements is pultrusion (for more details see CNR-DT 200/2004). The term pultrusion comes from the words *pull* and *extrusion*. The production process is completely automatic, with six easily controllable phases. During the process, it is important to control the position of the strengthening in the section. For this reason fibre and material, taken from their respective spools, flow into special guides prior to being inserted into the heated press where the resin is subsequently added.
The central web of the section is mainly constituted of fibres parallel to the longitudinal axes (*roving*), while the assembly of the section is given to the *mat*, with multi-directional fibres (orientated at 0°, 90° and $\pm 45°$) which completely wind around the pultrude. The fibres are then prevented from appearing on the surface by a *surface veil* which is also realised from multi-directional fibres. It has the function of protecting the pultruded element from surface lesions as well as increasing the resistance to chemical agents, UV rays and humidity.
A pultruded element can therefore present isotropic properties on the plane of the flat section (transversal isotropy) while, on the whole, it results highly orthotropic due to the stiffness and resistance being based on the long fibres in an axial direction.

Pultrudes used for structures, similar to metal ones, are constituted of flat sections, either L, U, T or I as well as I with wide flanges, tubular, etc.

9 APPENDIX C

9.1 TYPICAL TECHNICAL DATA SHEET OF FRP PULTRUDES

(1) A technical data sheet which lists the main mechanical properties of the FRP pultrudes is proposed in the following section. The technical data sheets currently available in commerce can include further information as well as only part of the information indicated here.
UNI EN 13706:2003 defines two classes of structural pultrudes, known as E17 and E23, which present effective flexural moduli equal to 17GPa and 23GPa, respectively.

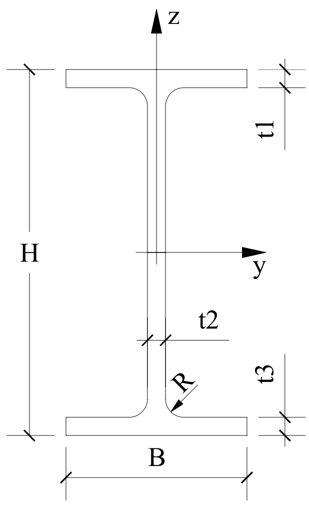
TYPICAL TECHNICAL DATA SHEET: pultruded elements for structural use

The manufacturer shall report the statistical values of the mechanical properties (e.g. sample mean, standard deviation, sample number, percentile, confidence interval).

Description
Commercial name, class EXX (§ 3.4.3 (2)), type of fibre, type of resin, manufacturing technology and any other information deemed useful.

Example of geometric and physical characterisation (Table 9.1-9.4)

Table 9-1 - Geometric characterisation.



Web/Flanges lengths (L_i)	Web/Flanges thickness (t_i)	Radii (R_i)	Section area (A)	Shear areas ($A_{V,y}$, $A_{V,z}$)	Moments of inertia (J_y, J_z)	Radii of inertia (r_y, r_z)	Resistance moduli (W_y, W_z)	Torsional stiffness factor (J_t)	Warping stiffness factor (J_ω)	Weight (P)

In every technical data sheet either the dimensional tolerances or a certification conforming to Appendix B of the regulations UNI EN 13706-2 should be indicated.
For non-double symmetrical sections to the items indicated above further information can be added in relation to: the position of the centroid moments and radii of inertia relative to the principal axes, position of the shear centre.

Table 9-2 - Physical characteristics.

Property		Measurement unit	Test method Reference standard	Note
Density		g/cm^3	ISO 1183-1:2004(E) ASTM D792	
Fibre content	weight	%	ISO 11667:1997(E)	
	volume	%		
Glass transition temperature of resin (T_g)		°C	ISO 11357-2:1999(E) (DSC) ISO11359-2:1999(E) (TMA) ASTM E1640 (DMA)	
Electrical conductivity		S/m	ASTM D149	
Thermal conductivity		W/(m·K)	ISO 8302 ASTM C177	

Table 9-3 - Mechanical properties to be determined through tests on a pultruded element.

Property	Symbol	Measurement unit	Test method Reference standard	Note
Effective modulus of elasticity	E_{eff}	GPa	UNI EN 13706-2	(1)
Effective shear modulus of elasticity	G_{eff}	GPa	UNI EN 13706-2	

(1) Required determination to classify structural pultrudes according to UNI EN 13706-3.

Table 9-4 - Mechanical properties determined through tests on samples of the material.

Property	Symbol	Measurement unit	Test method Reference standard	Note
Longitudinal tensile strength	f_{Lt}	MPa	UNI EN ISO 527-4; ASTM D638	(1)
Transversal tensile strength	f_{Tt}	MPa	UNI EN ISO 527-4; ASTM D638	(1)
Longitudinal compressive strength	f_{Lc}	MPa	UNI EN ISO 14126; ASTM D695	
Transversal compressive strength	f_{Tc}	MPa	UNI EN ISO 14126; ASTM D695	
Longitudinal flexural strength	f_{Lf}	MPa	UNI EN ISO 14125; ASTM D790	(1)
Transversal flexural strength	f_{Tf}	MPa	UNI EN ISO 14125; ASTM D790	(1)
Shear strength	f_{V}	MPa	UNI EN ISO 14130; ASTM D2344	(1)
Longitudinal bearing strength	f_{Lr}	MPa	UNI EN 13706-2; ASTM D953	(1)
Transversal bearing strength	f_{Tr}	MPa	UNI EN 13706-2; ASTM D953	(1)
Longitudinal modulus of elasticity in tension	E_{Lt}	GPa	UNI EN ISO 527-4; ASTM D638	(1)
Transversal modulus of elasticity in tension	E_{Tt}	GPa	UNI EN ISO 527-4; ASTM D638	(1)
Longitudinal modulus of elasticity in compression	E_{Lc}	GPa	UNI EN ISO 14126; ASTM D695	
Transversal modulus of elasticity in compression	E_{Tc}	GPa	UNI EN ISO 14126; ASTM D695	
Shear modulus of elasticity	G_{LT}	GPa	ISO 15310	
Poisson's ratio (longitudinal)	ν_{LT}		UNI EN ISO 527-4; ASTM D638	
Poisson's ratio (transversal)	ν_{TL}		UNI EN ISO 527-4; ASTM D638	

(1) Required determination to classify structural pultrudes according to UNI EN 13706-3.

<u>Storage Conditions</u>
Description of the storage conditions.
<u>Safety and handling precautions</u>
Description of the safety and handling precautions.

9.2 MATERIAL CHARACTERISATION TESTS

(1) The mechanical properties reported in Table 9-3 and Table 9-4 are, in general, obtained from short-term qualification tests.

(2)P Long-term tests can be carried out in order to analyse the evolution of the mechanical and physical properties.

(3) There are three types of behaviour over time in relation to:

- the phenomenon of chemical degradation;
- environmental factors (e.g. freezing/thawing cycles);
- load application manner: constant/variable.

Analysis of the long-term behaviour of the material subjected to a constant load requires *creep* tests. The reference regulation for the long-term tests on FRPs with a polymeric matrix is ISO 899-1:2003. In alternative, there is also ASTM D2990-01. The reference regulations for fatigue behaviour are ISO 13003-2003 and ASTM D 3479-02.
Appendix F of UNI EN 13706-2:2003 deals with the indications on how to carry out the tests to analyse the behaviour of FRPs subjected to the phenomena of chemical degradation and environmental factors.

10 APPENDIX D

10.1 CHOICE AND VERIFICATION OF FRP PULTRUDES: DUTIES AND RESPONSIBILITIES OF THE DESIGNER

(1) The manufacturers and/or suppliers should carry out appropriate quality controls. These include not only the production techniques of the pultruded element (e.g. pultrusion) but also all its elementary components. All the procedures and techniques used by the manufacturer should be systematically recorded and made readily available to any form of quality control.

(2) The products should be identified through the description, supplied by the manufacturer, of the material and all its elementary components, according to the criteria of traceability.

(3) The products should be accompanied by documentation certifying that tests have been carried out to measure the chemical, physical and mechanical characteristics of the material. The tests should be carried out by an independent third party, with proven experience in the filed of FRP products, in an appropriately equipped laboratory.

(4) The designer should:

- indicate the mechanical properties of the FRP pultruded element in the design;
- indicate the tests, with relative specific techniques, in order to verify several of the properties reported on the technical data sheet.

(5) The contractor and appliers should obtain FRP pultrudes with the characteristics indicated by the designer from manufacturers and/or suppliers who guarantee the quality of the product.

(6) The director of works:

- can request that tests be carried out on the products supplied in order to verify, taking into consideration the number of tests, the class declared by the manufacturer as well as to integrate the specifications indicated on the technical data sheet;
- can request that the tests be integrated with the specific techniques as defined by the designer.

(7) All the tests which define the chemical, physical and mechanical properties of the structural materials should be carried out and certified by officially recognised laboratories. This applies for all the tests of certification, qualification as well as acceptance. The officially recognised laboratories are regulated by the regulations in act.

(8) The inspector should:

- verify the quality of the material used through the accompanying certificates provided by the supplier;
- verify the acceptance of the material on behalf of the director of works;
- verify the results of any eventual acceptance tests requested by the director of works;
- carry out the further step required by the regulations in act.