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Design of robust and ductile FRP structures incorporating ductile adhesive joints

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ABSTRACT

A design concept for engineering structures consisting of brittle FRP components and ductile adhesive joints is proposed. The elastoplastic adhesive joints provide system ductility that compensates for the material ductility that FRP composites lack. In the elastic phase, the adhesive offers sufficient stiffness to provide continuity of stiffness over the joint, thus meeting the short- and long-term serviceability requirements for the structure. In the plastic phase, the adhesive develops a uniform stress distribution along the overlap length, thereby enabling sufficient joint rotation to provide an internal force redistribution that increases structural safety and robustness. The application of the design concept to a two-span FRP beam system with an elastoplastic hinge at mid-support showed an increase in structural robustness of almost 140% compared to a continuous FRP beam. FRP structures designed according to the proposed concept exhibit much higher structural safety than brittle structures without force-redistribution capacity.

1. Introduction

Fiber-reinforced polymer (FRP) composites, and particularly glass fiber-reinforced (GFRP) composites, are being considered with growing interest for applications in new primary load-bearing structures of bridges and buildings due to excellent material properties such as high specific strength, free formability, low thermal conductivity and – increasingly important – positive environmental aspects, such as low gray energy consumption (for GFRP) [1,2]. However, certain properties continue to hinder a widespread acceptance of these materials amongst structural engineers in the infrastructure sector. The lack of material ductility and difficult joining due to material anisotropy are particular drawbacks that must be overcome [3].

Against this background, Keller and de Castro [3] proposed a structural concept for FRP engineering structures that provides system ductility to compensate for the lack of material ductility. This concept includes the use of redundant structural systems and ductile adhesively-bonded joints. The ductile joints can compensate for the lack of material ductility of FRP components by providing ductility in the structural system, termed system ductility, which offers similar advantages to material ductility. Tailored ductile adhesives are envisaged, exhibiting an initial elastic behavior of sufficient stiffness to meet short- and long-term serviceability requirements. However, when serviceability or design loads are exceeded, adhesive behavior should change and become plastic or at least highly non-linear/inelastic with much lower stiffness. Furthermore, the elastoplastic or highly non-linear/inelastic behavior of the adhesives prevents the occurrence of high stress peaks. Shear and peeling stresses are much more evenly distributed along the bonded surface, leading to more robust joints less liable to premature and unexpected failure. If unexpected joint failure does occur however, the redundant (statically indeterminate) system offers alternative load paths and redistribution of cross-section forces due to the presence of other ductile joints, thus preventing structural collapse.

The authors proved the feasibility of the proposed concept through extensive experimental investigations on double-lap joints [4–6] and statically indeterminate two-span beam structures with integrated elastoplastic adhesive joints to form an elastoplastic hinge [3,6]. At mid-support, the beam flanges of the square-box cross-sections were connected with adhesive strap joints using highly non-linear/inelastic adhesives, as shown in Fig. 1 [3]. The ductile joints provided a favorable redistribution of the internal and external forces. In the case of adhesive joint failure, structural collapse was prevented thanks to system redundancy. Based on this work, a concept for the design of redundant FRP structures with ductile adhesive joints and adhesive choice is presented in this paper.

2. Design concept

2.1. Basis of design

The design concept is based on Eurocode limit state design philosophy using partial safety factors on the action and resistance

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Nomenclature

a	adhesive layer thickness
b	beam width
e	eccentricity between failure layer and cover plate axis
f_e	adhesive elastic stress
f_j	shear–tensile-interaction failure criterion
f_k	adhesive ultimate strength
h	beam height
k_j	joint stiffness
$k_{\theta,p}$	rotational stiffness of hinge
l	joint overlap length
t	beam flange thickness and cover plate thickness
t_f	adherend failure depth
$w_{k,c}$	beam deflection at UFS
$w_{SLS,c}$	beam deflection at SLS
E	full-section elastic modulus of beam
E_e	adhesive elastic modulus
E_p	adhesive plastic modulus
F_j	force in beam flange at mid-support at UFS
F_{rep}	representative value of action
G	full-section shear modulus of beam
G_e	adhesive elastic shear modulus
G_p	adhesive plastic shear modulus
$M_{e,j}$	elastic hinge moment SLS or ULS
$M_{k,c}$	characteristic bending resistance of FRP beam component
$M_{k,j}$	characteristic bending resistance of hinge
$M_{SLS,c}$	beam moment at SLS
M^-	hogging or negative moment at mid-support
M^+	sagging or maximum positive moment between supports
R_d	design value of resistance
$R_{d,c}$	design value of FRP component resistance
$R_{d,j}$	design value of joint resistance
R_k	characteristic value of resistance
$R_{k,c}$	characteristic value of FRP component resistance
$R_{k,j}$	characteristic value of joint resistance
S_d	design value of applied internal force
SLS	serviceability limit state
UFS	ultimate failure state
ULS	ultimate limit state
ε_e	adhesive elastic strain
ε_k	adhesive ultimate strain
γ_e	adhesive elastic shear strain
γ_k	adhesive ultimate shear strain
γ_F	load factor
γ_M	resistance factor
$\gamma_{M,adh}$	resistance factor of adhesive
$\gamma_{M,c}$	resistance factor of FRP component
$\gamma_{M,j}$	resistance factor of joint
κ_σ	tensile normal strength correction factor
κ_τ	shear strength correction factor
μ_r	robustness factor
ν	adhesive Poisson's ratio
σ_y	tensile normal stress at adherend failure depth
$\sigma_{y,k}$	characteristic adherend tensile normal strength
τ_e	adhesive elastic shear stress
τ_k	adhesive ultimate shear strength
τ_{xy}	shear stress at adherend failure depth
$\tau_{xy,k}$	characteristic adherend shear strength
Δl_p	elongation of joint overlap in Phase II
Δu_j	joint elongation increment
ΔF_j	joint axial load increment
$\Delta\gamma_p$	adhesive shear strain of plastic range
$\Delta\theta_p$	rotation angle over mid-support in Phase II
$\Delta\tau_p$	adhesive shear stress of plastic range

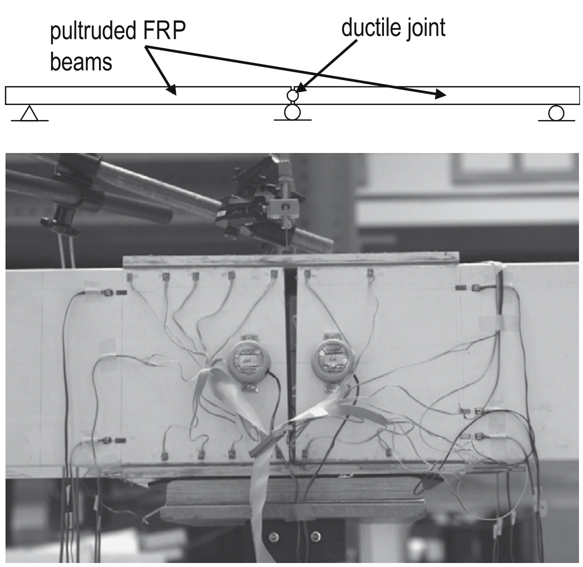

Fig. 1. Two-span FRP beam with elastoplastic strap joints over mid-support (beam span 2×3.60 m, square-box cross-section $240 \times 240 \times 12$ mm^3, overlap length cover plates 200 mm) [3].

sides. The structural behavior is characterized by three states: serviceability limit state (SLS, normally stiffness-governed), ultimate limit state (ULS, comparing design values of actions with resistances) and ultimate failure state (denominated UFS), representing effective structural collapse (assumed here to occur at the characteristic resistance values). Accordingly, the following condition should be satisfied at ULS:

$$S_d = S(\gamma_F \cdot F_{rep}) \leqslant R_d = \frac{R_k}{\gamma_M} \tag{1}$$

where S_d = design value of applied internal force, R_d = design value of resistance, F_{rep} = representative value of action, R_k = characteristic value of resistance (95% fractile value), γ_F = load factor, and γ_M = resistance factor.

To achieve full system ductility, the ductile joint resistance should be higher than the brittle FRP component resistance as follows:

$$R_{d,j} = \frac{R_{k,j}}{\gamma_{M,j}} \geqslant R_{d,c} = \frac{R_{k,c}}{\gamma_{M,c}} \tag{2}$$

where subscript-j denotes the joint and subscript-c the FRP component. Resistance factors for FRP components and adhesive joints can be adopted from EuroComp [7] or from [8]. For pultruded FRP components, the value varies for short-term loading between 1.27 and 1.65 (depending on the source of material properties) and for adhesives between 1.56 and 3.12 (mostly depending on serviceability conditions) [7]. A resistance factor for joints (which exhibit fiber-tear failure in the adherend) of 1.34 is recommended in [8].

2.2. Ductile adhesive behavior

A visco-elastoplastic/ductile and visco-elastic/brittle stress–strain behavior of adhesives is defined in [4]. Adhesives exhibiting