Damage modelling of adhesive joint in composite reinforced metallic beams

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ABSTRACT: A new method for repair or strengthening of metallic structures has been developed and investigated during the recent years. The traditional way of upgrading metallic beam elements have been by use of additional metallic plates, which have been either bolted or welded to the existing substrate. The new method involves use of advanced composite plates, usually made of unidirectional carbon fibre reinforced polymers (CFRP). The CFRP plates are adhesively bonded to the metallic beam to reduce the stresses in the tension area of the steel element. Today, there are no established codes or standards for structural design of externally reinforced metallic beams in civil engineering. However, different approaches have been recommended in order to accurately determine the CFRP/Adhesive/Steel interfaces strength properties. The present paper focuses on the finite element modelling of steel specimens reinforced with CFRP where the adhesive is modelled with cohesive interface elements. Results from three experimental tests are compared to those obtained from numerical analysis.

1 INTRODUCTION

The present study focuses on the design of the adhesive joint with reference to debonding near the end of the CFRP plate. Irrespective of which load combination acting on the beam causing a bending moment, a concentration of interfacial shear and peeling stresses will appear in the bond line near the end of the CFRP. These stresses have to be carried by the resistance of the compositely acting materials, either the adherents or the adhesive.
For metallic beams reinforced with adhesively bonded CFRP plates on the tension side, two different approaches are developed for predicting the capacity of the adhesive joint, namely the stress based method and the fracture mechanic based method. These methods were introduced earlier by Linghoff & André (2008). In this study, the focus will be on the second method, especially on the comparison of experimental results with results from Finite Element model using cohesive interface elements and fracture energy based material model for the adhesive joint. Two different approaches are available for design of adhesive joint in civil engineering using the linear elastic fracture mechanic. One is the energy release rate approach and the other is the stress intensity factor approach. In existing guidelines, for design of adhesive joints in CFRP reinforced metallic beams, an energy based method founded on the energy release rate approach is considered. The energy release rate approach considers the energy released during the propagation of the crack along the adhesive joint, and the method inherently takes account to the existence of stress discontinuities. The design philosophy is that the fracture energy release rate (G), which also can be denoted crack extension force or crack deriving force, during propagation of the crack is obtained

and compared with the critical energy release rate (G_C) and the criterion is that $G \geq G_C$. Finite element models based on fracture energy have been conducted on double shear lap specimens and successful results were reported (Bocciarelli et al. (2007)).
From a review of available design approaches, it is noticeable that there is lack of knowledge in the field of analysing and design of adhesively bonded elements in structural engineering, and this is reflected by the use of high partial factors. Additionally, there is no general agreement of which design method that is the most suitable to obtain a sufficiently good design. In the present investigation a fracture mechanic model, based on cohesive elements, has been developed. One of the major aims with this investigation was to obtain information about how well the available cohesive elements implemented in ABAQUS can be used to model the real behaviour and failure of an externally CFRP reinforced structural element loaded in bending. Another objective was to determine experimentally a material model for the adhesive that can be use to model different type of specimens.

2 EXPERIMENTAL SET-UP

It has been observed and reported that crack often occur close to the interface adhesive/steel in a CFRP reinforced metallic beam (Bocciarelli et al. (2007)). Similar observations were made in the experiments reported further (see Figure 8). Therefore, the stress-deformation relations (cohesive laws) for the epoxy adhesive layer were determined experimentally for the system steel/adhesive/steel for mode I and II experimentally. Double Cantilever Beam (DCB) tests and End Notched Flexural (ENF) tests have been performed in collaboration with the University of Skövde. The results give information about the strength and the fracture energy for mode I and II. The obtained results are used as input data for the cohesive elements layers material model.

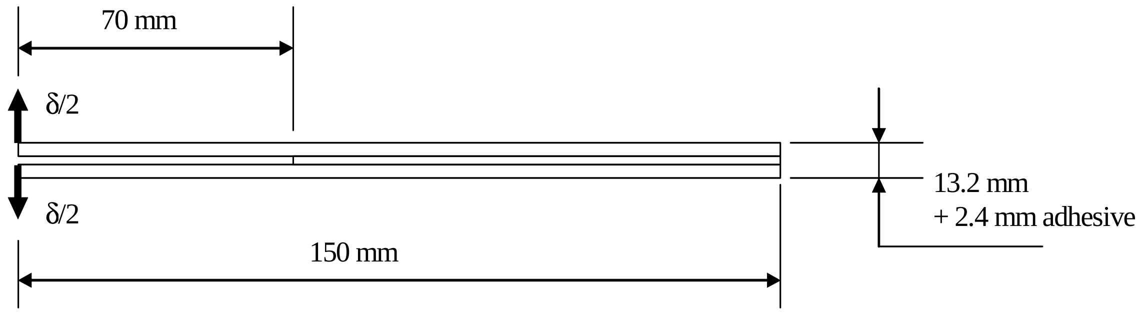

Figure 1. DCB, dimensions and geometry.

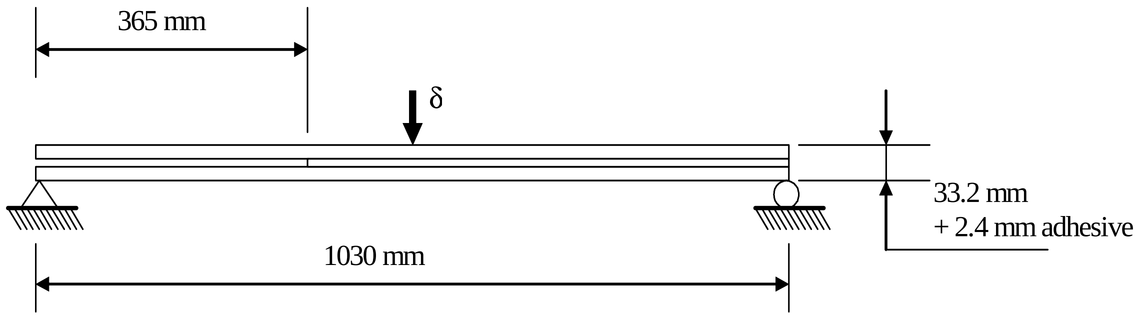

Figure 2. ENF, dimensions and geometry.

In order to verify the bonding efficiency of different systems Primer/Adhesive/Steel/CFRP prior to full-scale tests (Tensile tests on steel reinforced CFRP), small-scale 3 point bending experiments were performed with 3 different systems. These tests were performed with the ambition to evaluate failure mechanisms in the three systems. These three different systems are denoted A, AP and B, which stands respectively for reinforced system A with and without primer, and reinforced system B. The specimens are CFRP reinforced steel which geometry is shown in Figure 3-a.
Tensile tests were also performed on CFRP reinforced steel specimens. Steel beams were reinforced on two sides with CFRP (reinforcement system B only). The geometry is shown in Figure 3-b.

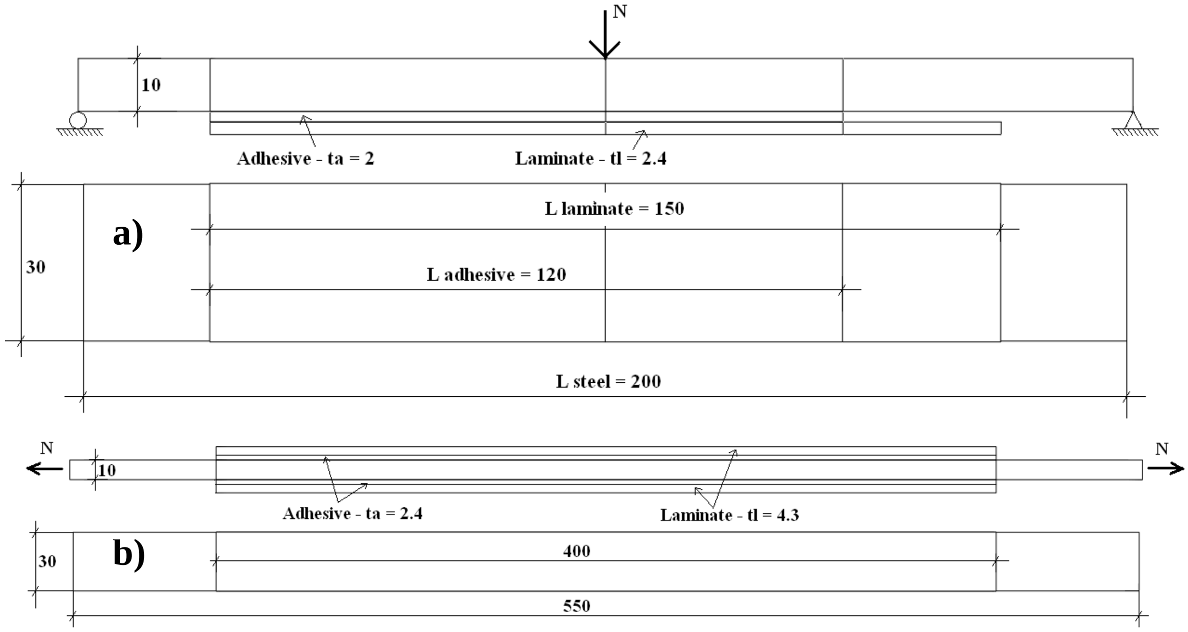

Figure 3. Experimental test set-up: a) 3 point bending test and b) Tensile test

3 FINITE ELEMENT STUDY

3.1 *Cohesive zone modelling*

Cohesive elements implemented in the commercial finite element package ABAQUS can be represented as two cohesive surfaces separating from each other under shear or/and normal stresses. In this study, the bilinear traction separation law is defined by a linear elastic response, a strength criteria and a damage evolution law based on energies. The use of cohesive elements together with a traction separation law (TSL, see Figure 4) is briefly described in the following part of the report. Detailed descriptions of cohesive elements in ABAQUS are available for the reader in ABAQUS user manual (2007).

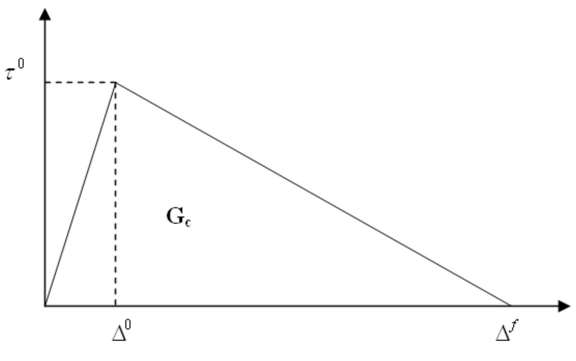

Figure 4. Bilinear traction separation law

The damage initiation starts when a quadratic stress criterion is fulfilled. The strength of the adhesive in the normal and shear directions are used as input data.

$$\left(\frac{\sigma_{33}}{\hat{\sigma}_{33}}\right)^2 + \left(\frac{\tau_{13}}{\hat{\tau}_{13}}\right)^2 + \left(\frac{\tau_{23}}{\hat{\tau}_{23}}\right)^2 = 1 \quad (1)$$

The adhesive layer is most likely mixed mode loaded, i.e. we have a contribution of mode I and II in the failure process. The damage propagation is studied in term of energy release rate and fracture toughness. In order to accurately predict the mode mixity of the epoxy under loading (Camanho & Davila (2002), the Benzeggagh-Kenane criteria BK is used (Benzeggagh & Kenane (1996)).

$$G_{Ic} + \left(G_{IIc} - G_{Ic}\right)\left(\frac{\beta}{1+2\beta^2 - 2\beta}\right)^{\eta} = G_{mc} \tag{2}$$

with

$$\beta = \frac{\Delta_{shear}}{\Delta_{peel} + \Delta_{shear}} \tag{3}$$

where G_{Ic} and G_{IIc} are the fracture toughness in mode I and II respectively. The exponent η is chosen to 1.5. β is the parameter determining the mixed mode ratio based on the current values of the peel and shear opening in the TSL for mode I and II respectively.

It was observed from the finite element analysis that the mixed mode ratio was varying depending on the position along the bond line.

The softening part of the traction separation curve is defined as linear by a damage parameter D.

$$D = \frac{\Delta^{f}.\left(\Delta^{\max} - \Delta^{0}\right)}{\Delta^{\max}.\left(\Delta^{f} - \Delta^{0}\right)} \tag{4}$$

with

$$\Delta^{f} = \frac{2G_{mc}}{\tau^{0}} \tag{5}$$

3.2 *Finite element models*

All three tests specimens were modelled using ABAQUS. The FE models were performed in the following order. Firstly, the DCB and ENF models were conducted to verify the possibility to use cohesive elements for thick adhesive. When this verification was completed successfully the same method was employed in the analysis of the 3- point bending and tensile tests specimens.

The three FE models considered are shown in Figure 5.

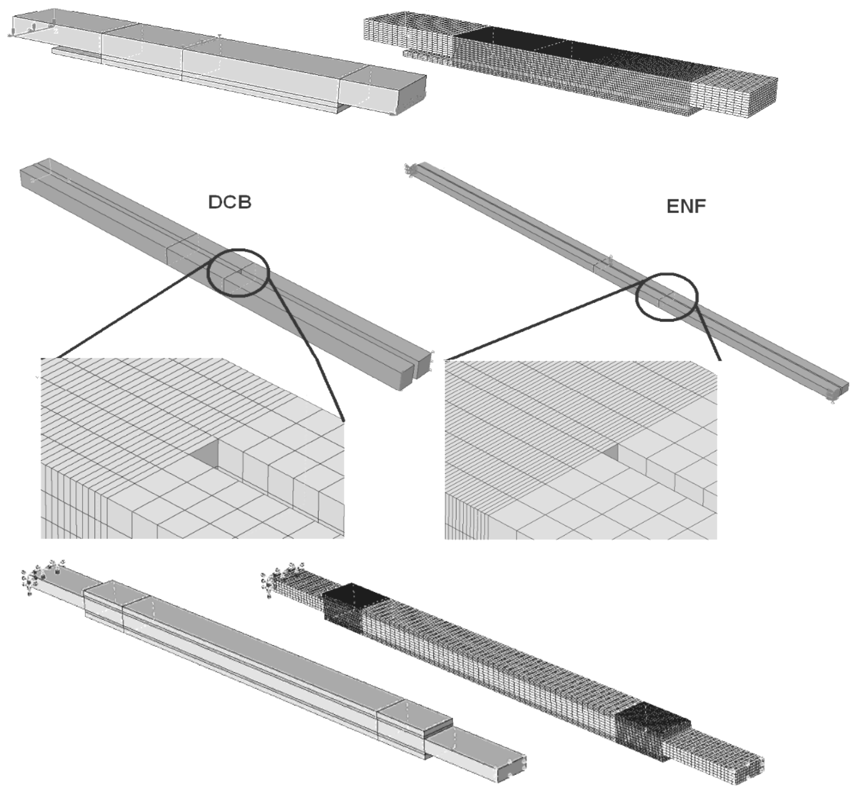

Figure 5. Finite element models for 3 point bending, DCB, ENF and tensile tests

In all models, C3D8 8-nodes linear brick elements were used to model the CFRP and the steel parts. The adhesive layers were modelled using COH3D8 8-nodes three-dimensional cohesive element, with one element through the thickness. Surface based tie constraints were applied at interfaces adhesive/CFRP and adhesive/steel. The materials used are reported in Table 1. The CFRP is considered as isotropic to simplify the models since no major differences were observed in the global response (load-displacement) when using orthotropic material model (Figure 6).

Table 1: Materials – elastic properties

	E (GPa)	υ		E (GPa)	υ
Adhesive	7	0.3	CFRP – tensile experiment	383	0.3
Steel	210	0.3	CFRP – bending experiment	210	0.3

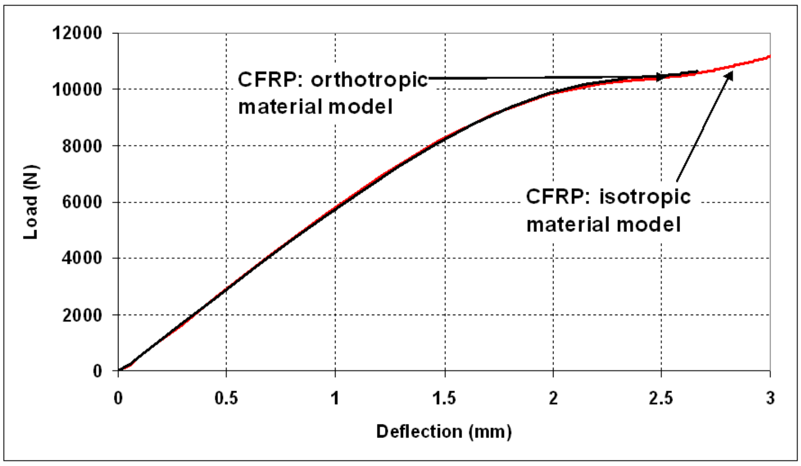

Figure 6. Bending specimens: material model 1, orthotropic and isotropic CFRP material model

G_{Ic} and G_{IIc}, fracture energy in mode I and II respectively, were obtained from DCB and ENF tests and are equal to 1070 N/m and 3644 N/m. The peak stresses were 19.4 MPa (peel, DCB) and 27.4 MPa (shear, ENF).

Apart from DCB and ENF FE models results, higher loads at failure were reported when the material model for the adhesive was taken directly from the DCB and ENF experimental results. This is graphically represented in the results part further. Therefore, a material model parameter study where both the fracture energies and strength input are modified is carried out. 8 models are built as reported in Table 2. The percentage in the column and in the row is relative to the results from DCB and ENF experiments, where 100% means “experimental results”.

Table 2: Adhesive material models: Parameter study for bending specimen FE model

	100% G_{ic}	80% G_{ic}	60% G_{ic}	40% G_{ic}
100% strength	Model 1	Model 2	Model 3	Model 4
75% strength	Model 5	Model 6	Model 7	Model 8

4 RESULTS AND DISCUSSIONS

Both DCB and ENF were modelled and the results are reported in Figure 7. These FE models were conducted in order to validate the FE-model methodology. The adhesive material model is model 1, i.e. the real experimental value from DCB and ENF tests. Very good accuracy is reported for the 2 models, which indicates that cohesive elements can be used for thick adhesives. However, the stress variation along the adhesive thickness can not be capture, since only one element is used through the thickness.

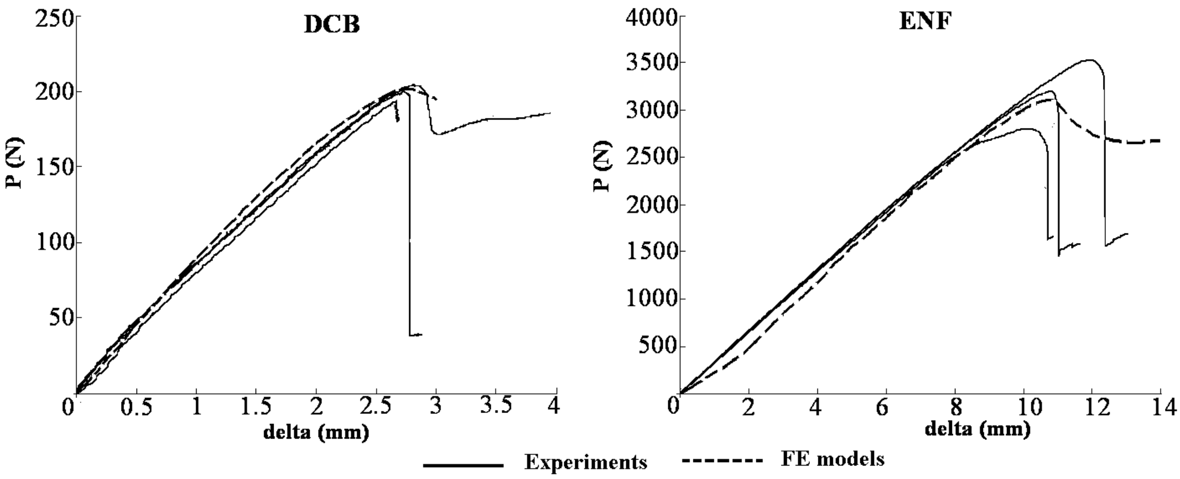

Figure 7. Load displacement curves for DCB and ENF specimens: FE models and experiments

The bending test experiment showed that specimens failed in the adhesive at an approximate load of 5 kN, see Figure 8. One can see that using material model 1 overestimates the load at failure by a factor of 2 (Figure 9). The use of material models 4 and 8 yields results much closer to the experimental ones.

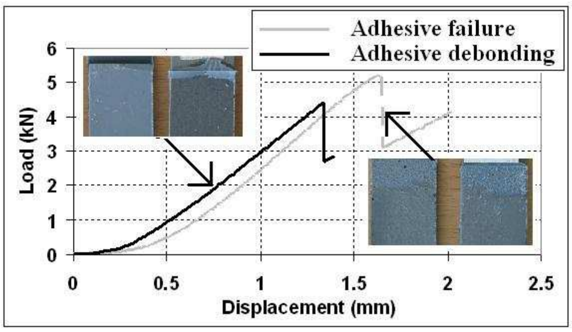

Figure 8. Load displacement curves for 3 point bending specimens: Experiments

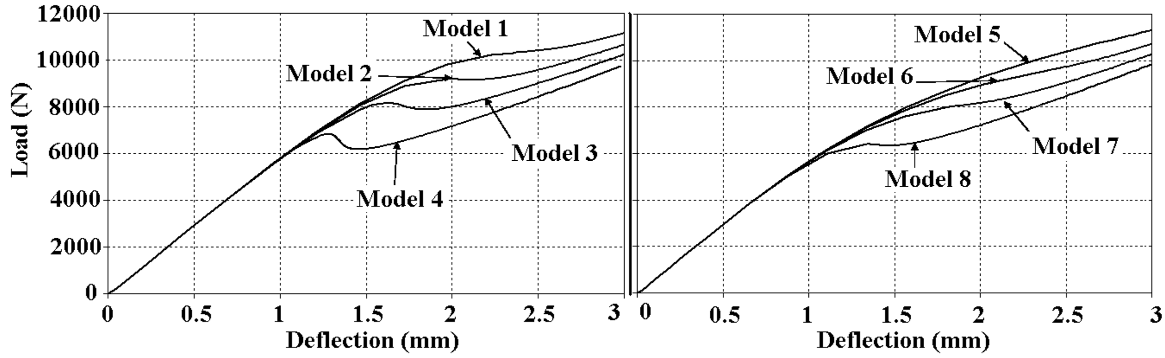

Figure 9. Load displacement curves for 3 point bending specimens: FE models

Two FE models of the tensile test are then built, one with material model 1 for the adhesive, the other with material model 8. Figure 10 shows the results from the FE models and from the experiments. One can see that as for the bending test model, the load at failure is doubled when the adhesive is modeled using cohesive laws obtained from DCB and ENF. Material model 8 yields good results as previously observed for the bending test FE model.

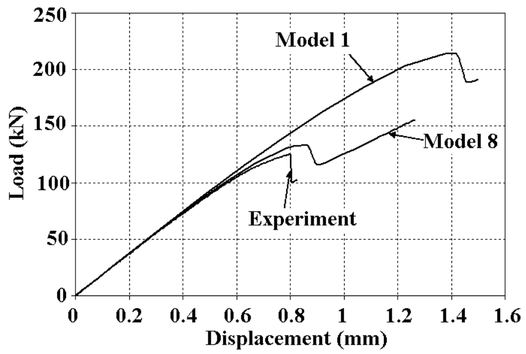

Figure 10. Load displacement curves for tensile tested specimens: FE models and experiments

It has been demonstrated that the cohesive laws obtained from DCB and ENF can be used to accurately model DCB and ENF experiments in ABAQUS. However, even if the crack occur at the interface steel adhesive, it appears that cohesive laws from steel/adhesive/steel DCB and ENF experiments overestimate the load at failure, due to high fracture energies. Cohesive laws proper to the system Steel/Adhesive/CFRP are needed to model CFRP reinforced steel. It is very interesting to point out that the same adhesive material model could be used to model with a relatively good accuracy both bending and tensile tests.

5 CONCLUSIONS

Cohesive elements implemented in the commercial finite element software ABAQUS have been successfully used to model a thick adhesive (2 mm) in DCB and ENF specimens.
For both 3 point bending and tensile experiments of CFRP reinforced steel beams, failure occurs in the adhesive close to the interface adhesive/steel. It was shown that the damage initiation load was overestimated when raw data from DCB and ENF experiments were used as input in the FE models.
An empirical material model for the adhesive giving accurate results for the 3 point bending specimens FE model was used as input to model the tensile test and yields results in good agreement with experiments.
Even if failure mostly occur at interface steel/adhesive in CFRP reinforced metallic beams, cohesive laws for mode I and II for the system steel/adhesive/steel (DCB and ENF) are not yielding accurate results.

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