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Numerical Analysis of the Anchoring with U-Jackets of FRP Flexural Strengthening of Beams

Dissertação de Mestrado em Reabilitação de Edifícios orientada pelo Professor Doutor Paulo Manuel Mendes Pinheiro da Providência e Costa e Pelo Professor Doutor Ricardo Joel Teixeira Costa.

July, 2019

Faculdade de Ciências e Tecnologia
da Universidade de Coimbra

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Contents

1. Research Framework

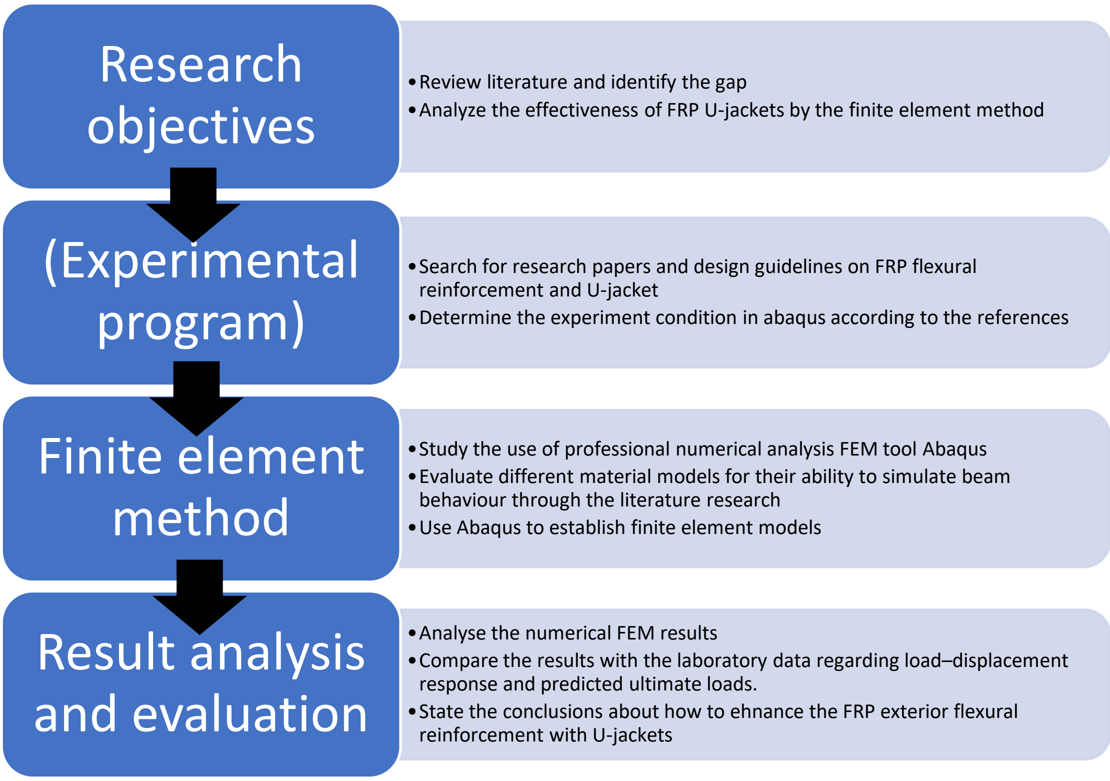

Figure 1 - Research framework

The research framework includes four steps. Firstly, the research objectives should be clearly identified through a comprehensive analysis of the research topic and a review of literature in the related field. A major objective is therefore produced, which is to analyse by the finite element method the effectiveness of FRP U-jackets in preventing the debonding of the FRP exterior flexural reinforcement. Secondly, I should build up an understanding of the experimental programs performed by other authors. This will be achieved by reading and analysing the literature and design guidelines on FRP exterior flexural reinforcement and U-jacket. In the end of this second process, the experimental condition is established with the help of the selected literature. Thirdly, it is to apply finite element method. The success of this step has two prerequisites: the learning process for the professional numerical analysis FEM tool Abaqus, as well as the evaluation of different material models for their ability to simulate beam behaviour through the literature research. Next the numerical model will be built and the analysis performed. Finally, the results should be analysed by comparing them with the laboratory data regarding load–displacement response and predicted ultimate loads. And only then could the final conclusions about the application of U-jackets to enhance the FRP exterior flexural reinforcement of beams be stated.

2. Introduction

The external application of FRP (Fiber Reinforced Polymer) strips is one of the best options for the flexural strengthening of reinforced concrete beams, for several reasons such as reduced intrusion level and ease of installation. However, from the strength of materials point of view, this type of reinforcement of reinforced concrete beams has two main difficulties associated to (i) the concrete cover lacking bracing to resist the tension stress introduced by the FRP laminates and (ii) the high risk of debonding, namely in the vicinity of cracks in the concrete cover. The application of anchorages to those FRP strips can not only boost members' deformability, ductility, and strength, but also postpone FRP debonding failure. Considering the fact that the advantages of anchorage solutions of the FRP exterior flexural reinforcement are widely accepted among researchers, it is necessary to pursue further investigation to establish reliable design formulae.

One of the oldest types of FRP anchorage systems is metallic anchorages. Due to their rigidity and the capacity of mechanical fasters to efficiently withstand tensile and shear forces, they can provide a significant enhancement in anchorage strength. However, the drilling of threaded tubes or anchors for expansion into concrete might cause damage to the existing structure and is a time-consuming job. In addition, there are concerns on the cost of this option and its long-term durability.

Externally bonded FRP U-jackets is a feasible option due to its corrosion resistance and ease of installation. Furthermore, FRP U-jackets also have a considerably higher anchorage strength than other non-metallic anchor devices. The objective of this dissertation is analysing the effectiveness of FRP U-jackets as an anchoring device by the finite element method.

2.1 Research question

Based on the design guidelines, existing references and the recommendation from the supervisors, the following research question was formulated.

How to use finite element method to analyse the effectiveness of FRP U-jackets ?

Only a relatively small percentage of research have examined the efficacy of FRP U-jackets. Furthermore, almost none of the researchers used the finite element method to simulate the behaviour of FRP U-jackets as anchorage device.

2.2.Aims and objectives

This research aims to fill the gap by providing a numerical model and applying this model. This project is aspired to enrich the study of FRP U-jackets.

The objectives of this dissertation are listed below.

- Choosing the finite element analysis method
- Finding experimental results about FRP U-jackets
- Selecting the appropriate concrete material model
- Selecting the appropriate FRP material model
- Selecting the appropriate steel reinforcement material model
- Finding a way to simulate the interaction between the FRP strips and jackets and concrete
- Choosing the appropriate elements for each part in the model
- Establishing the entire finite element model
- Analysing the result and compare with the experimental data
- Establish practical guidelines

2.3 Work Product

Finite element model – It should be capable of simulating the behaviour of the FRP U-jackets and longitudinal laminates in this analysis.

Final report – Deliver a detailed explanation and result analysis for the finite element model and main conclusions.

2.4 Beneficiaries

Through this dissertation, it is intended to produce reliable finite element model for the following groups of potential beneficiaries:

- **Company**- This dissertation provides the possibility for some companies to find a safer and more economical and efficient way to rehabilitate reinforced concrete beams.
- **Researchers**- This dissertation may provide some insights for researchers who intent to analysing the effectiveness of FRP U-jackets as anchorage device.

2.5 Work plan

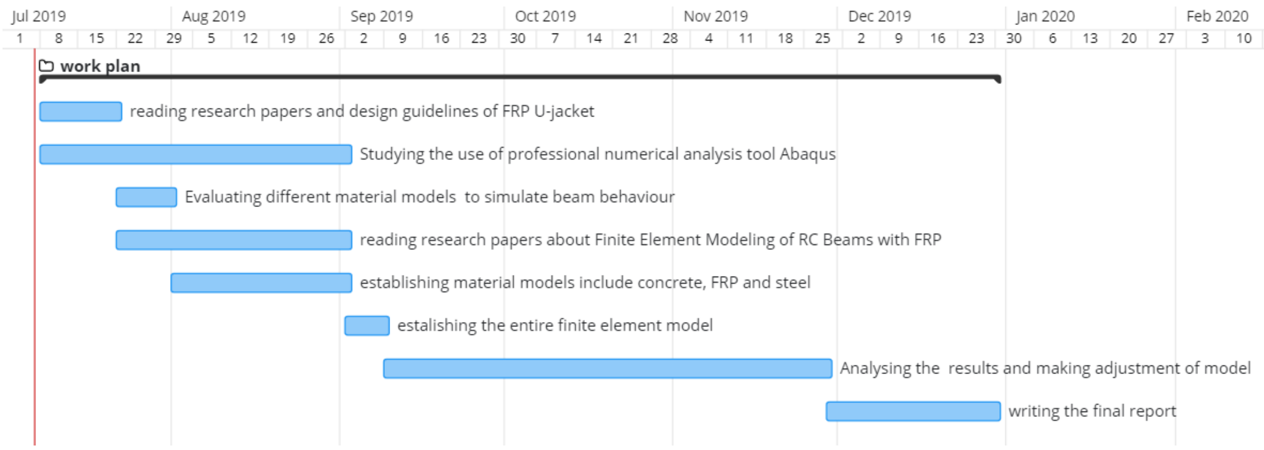

Figure 2 - Gantt chart

2. Methodology

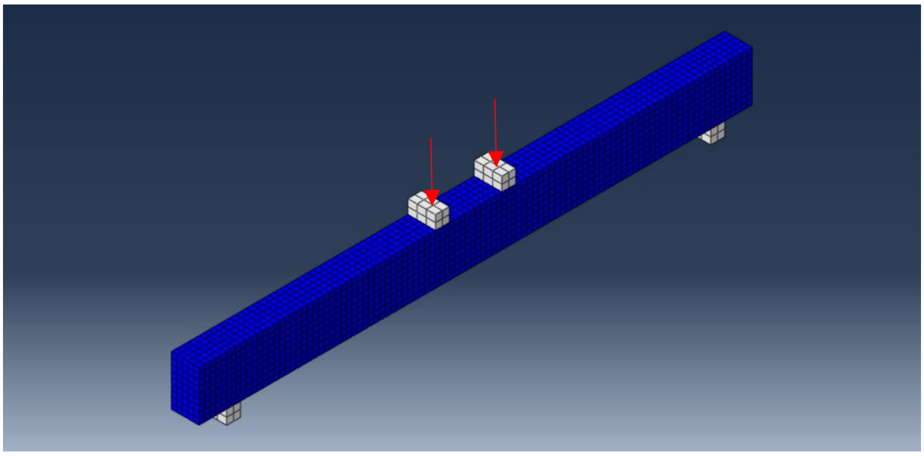

Figure 3- Experiment setup in Abaqus

3.1 Material properties and constitutive models

The professional numerical analysis FEM tool Abaqus was used, evaluating different material models for their ability to simulate beam behaviour. A linear isotropic and orthotropic elastic models were used for the FRP and a cohesive bond model for the concrete–FRP interface. A plastic damage model has been used for the concrete.

3.1.1 Finite element analysis product

ABAQUS/Explicit can accurately simulate the reinforced concrete structure response based on solving the convergence problem caused by material failure and damage (Wang, 2009).

3.1.2 Concrete

The plastic-damage model suggested by Lubliner et al. (1989) and Lee and Fenves (1998) is designed mainly to provide a particular capacity for analysing concrete structures under cyclic or dynamic loading, which could correctly simulate concrete failure in this analysis.

3.1.3 FRP

In this research, two distinct FRP models will be used. The FRP material is regarded as linear isotropic elastic until failure in the first model. In the second model, the FRP is modelled as a linear elastic orthotropic material.

3.1.4 Steel reinforcement

In tension and compression, steel is presumed to be an elastic-perfect plastic material. And it is assumed that the bond between reinforcement of steel and concrete is a perfect bond.

3.1.5 FRP-concrete interface

The cohesive model suggested by Obaidat, Y. T. (2010) can represent the bond behaviour between FRP and concrete.

3.2 Experimental program

This dissertation presents a finite element analysis that is validated against laboratory tests of six beams carried out by F.Ceroni (2010). All beams have the same rectangular cross-section and were subject to the four-point bending flexural test. Beam 1 was tested without FRP flexural reinforcement to be used as a benchmark. Beam 4 has vertical U-shaped strips wrapping of the section at both ends; beam 6 have 45º inclined U-shaped strips, while beam 5 has the same U-shaped strips distributed along the whole length. In contrast, beams 1, 2 and 3 have no end anchorage devices.

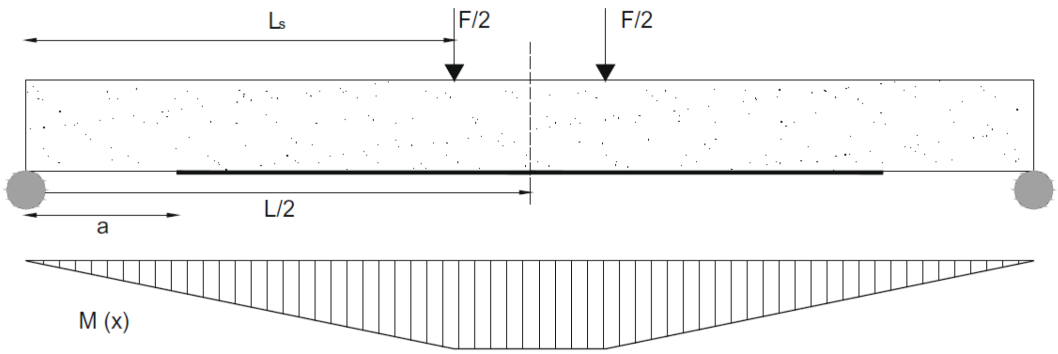

Figure 4 - Experiment setup and loading scheme by F.Ceroni (2010)

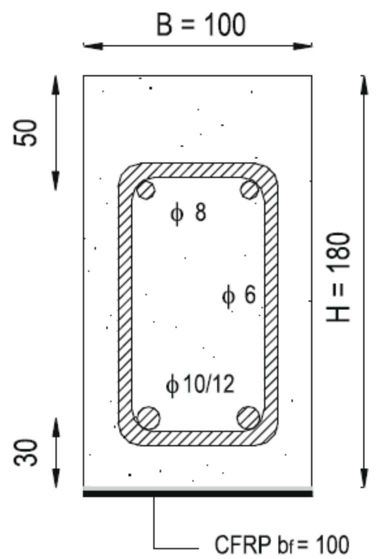

Figure 5 - cross section of beam F.Ceroni (2010)

Beam	a (mm)	L_s (mm)	A_f(mm)^2	n_f	Anchorage
1	-	880	0.0	0	No
2	300	880	16.7	1	No
3	300	880	33.4	2	No
4	300	880	16.7	1	Yes
5	300	880	16.7	1	Yes
6	300	880	16.7	1	Yes

Table 1 - Geometric properties of beams

A_f – area of FRP laminate

L_S – shear span of the beam

n_f – number of FRP layers attached to the beam

a – distance from the end of the FRP laminate to the support

3.3 Results analysis and evaluation method

The analyses results will be compared with the experimental data from F.Ceroni (2010) regarding load–displacement response and predicted ultimate loads. Drawing the load-deflection curves of all beam samples and comparing them with the experimental data respectively. If the model is incorrectly correlated with the experimental data, it will be necessary to analyse the cause and revise the model appropriately.

4. Literature review

4.1 FRP U-jackets

Only a relatively small percentage of research (Ritchie et al. 1991; Smith and Teng 2003; Piamanmas and Pornpongsaroj 2004; Ceroni 2010; Kalfat et al. 2013; B.Fu and J.G.Teng 2016) has examined the efficacy of FRP U-jackets in mitigating concrete cover separation failure in reinforcement concrete beams retrofitted with FRP laminates. All these researches except Piamanmas and Pornpongsaroj (2004) were performed using FRP U-jackets as a secondary consideration to prevent concrete cover separation. In particular, Ritchie et al. (1991) carried out an experimental program composed of 16 samples. The experimental factors included the FRP laminates' thickness, width, and length, fiber direction, and end anchorage devices. It was found that the use of U-jackets achieved a greater load-carrying capacity of beams, but samples with U-jackets still failed by the separation of concrete cover.

Smith and Teng (2003) conducted an experimental study primarily to explore the effect of shear and bending at the FRP laminates on concrete cover segregation. Four samples included a U-jacket to mitigate concrete cover separation among the 12 experiments performed by Smith and Teng (2003). The findings of these four experiments revealed that the use of vertical FRP U-jacket at the end of the FRP laminates contribute to some improvement of the failure load, but the improvement rate was quite restricted. Only four small-scale beams with end anchorage devices were tested by Piamanmas and Pornpongsaroj (2004); moreover, all their beams contained strong U-jacket anchorage, so the test findings did not shed light on the number of U-jacketing required to prevent concrete separation.

Ceroni (2010) tested 13 beams reinforced with FRP. Two samples retrofitted with vertical FRP U-jacket(s) (i.e. one vertical FRP U-jacket at the end of the FRP laminates in Sample A5 and five uniformly distributed vertical FRP U-jackets in Sample A7) shared a control specimen (i.e. Sample A2), which was only reinforced with an FRP laminates and failed by concrete cover separation. Comparison between these two beams and their control specimen showed that concrete cover segregation was suppressed by the use of vertical FRP U-jacket(s), resulting in strength rises of 51% and 39%, as well as midspan deflection increases of 47.2% and 17.2%, respectively, for specimens A5 and A7.

4.2. Fnite element method

Wang, (2009) set an RC cantilever as an example to verify the applicability and validity of ABAQUS/Standard and ABAQUS/Explicit in reinforced concrete structures simulation. It was found that ABAQUS/Explicit can accurately simulate the reinforced concrete structure response based on solving the convergence problem caused by material failure and damage. The simulation method can reduce the difficulty of convergence due to negative stiffness, reduce the computer computing cost, and shorten the calculation time.

The plastic-damage model suggested by Lubliner et al. (1989) and Lee and Fenves (1998) was designed mainly to provide a particular capacity for analysing concrete structures under cyclic or dynamic loading, which could correctly simulate concrete failure in this analysis.

Obaidat, Y. T. (2010) developed a cohesive model to represent the bond behaviour between FRP and concrete. The debonding failure mode and the predicted maximum loads were in excellent correlation with the experimental work.

4.3 Design guidelines

The installation of vertical FRP U-jackets at laminates ends has been frequently defined in current design rules as the anchorage [ACI 440.2R (ACI 2008), GB 50608-2010 (China Planning Press 2010), and Concrete Society (2012)] despite the inadequacy of studies on the efficacy of this type of FRP end anchorage devices. The ACI Guide Document (ACI 440.2R) contains a provision for designing FRP U-jacket anchorage to prevent concrete cover separation on the basis that the transverse force resisted by the

U-jacket(s) at the end of the plate is equivalent to the force from the bonded FRP laminates at failure.

This principle was only based on three beam samples test results (Reed et al. 2005). The Guide Document published by the Concrete Society of the United Kingdom (2012) provides an expression of a comparable type but with distinct coefficients to determine the area of vertical FRP U-jackets. The Chinese National Standard GB 50608-2010 demands a prescriptive detailing requirement for the use of FRP U-jackets, but no design calculations are recommended. These provisions have been established on a very restricted study basis and therefore there are strong doubts about their reliability. Fu and Teng (2016) evaluated the relevant provisions in three existing design guidelines, having concluded that they are highly conservative. In particular, the amounts for vertical FRP U-jacketing demanded by ACI 440 and TR55 are excessive.

5.Current progress

A simple support RC beam model was created in Abaqus as a control beam. The test performed by applying displacement-controlled loading with 0.05mm/s loading speed. The figures below show the tensile damage of concrete during the experiment.

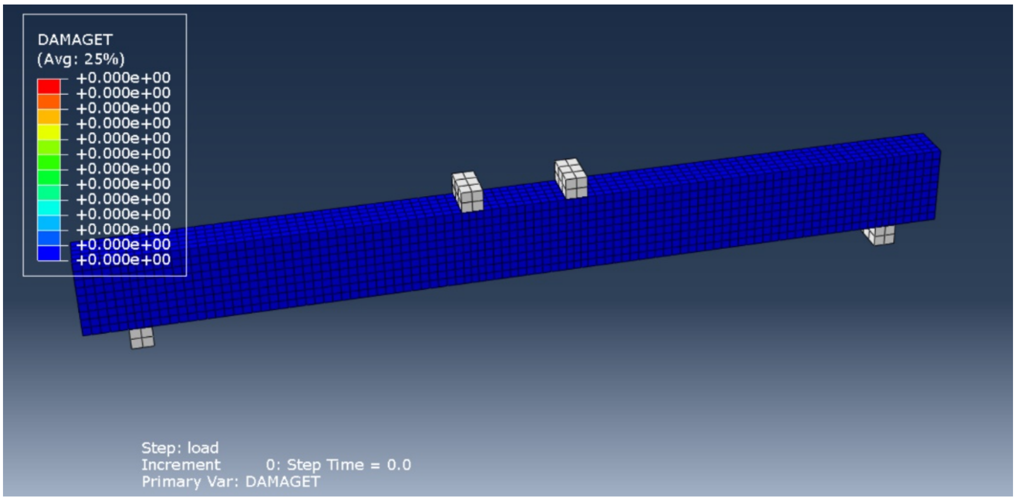

Figure 6 – Test setup

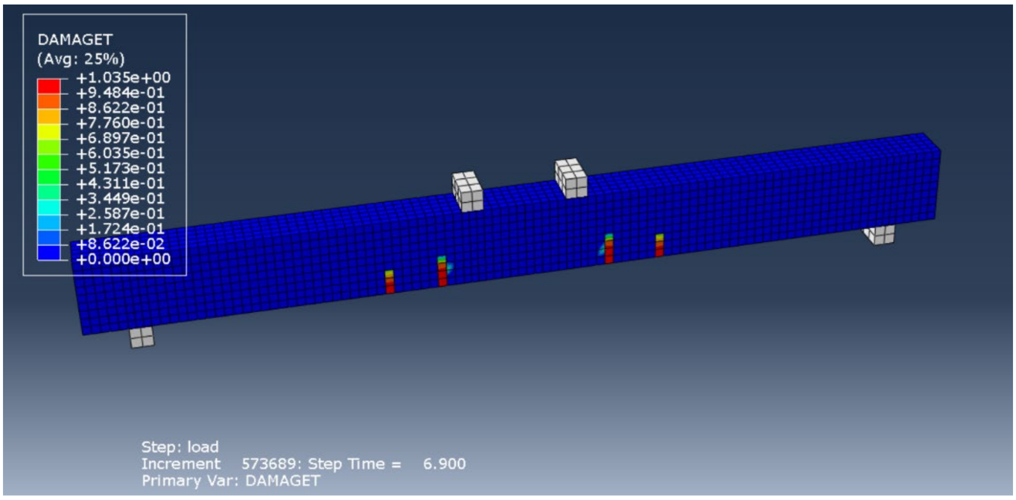

Figure 7 – Appearance of cracks

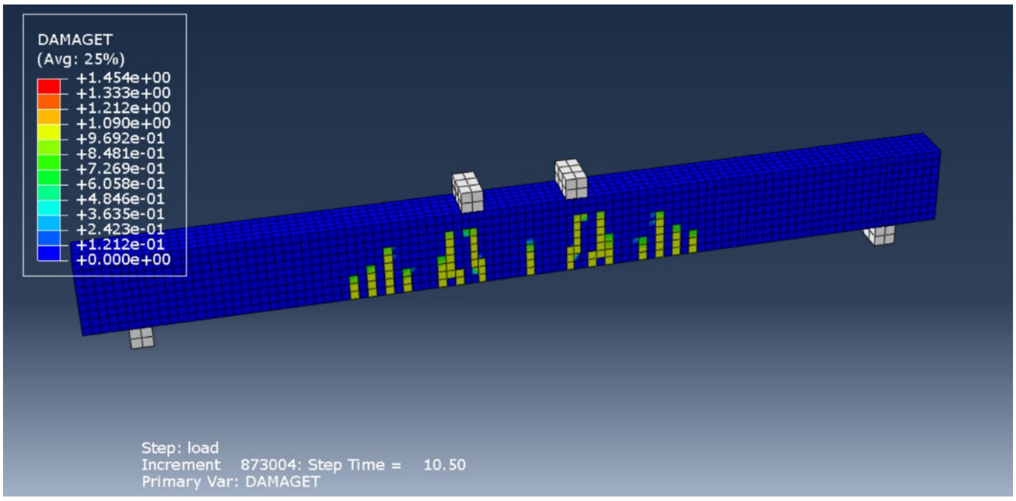

Figure – Development of the cracks

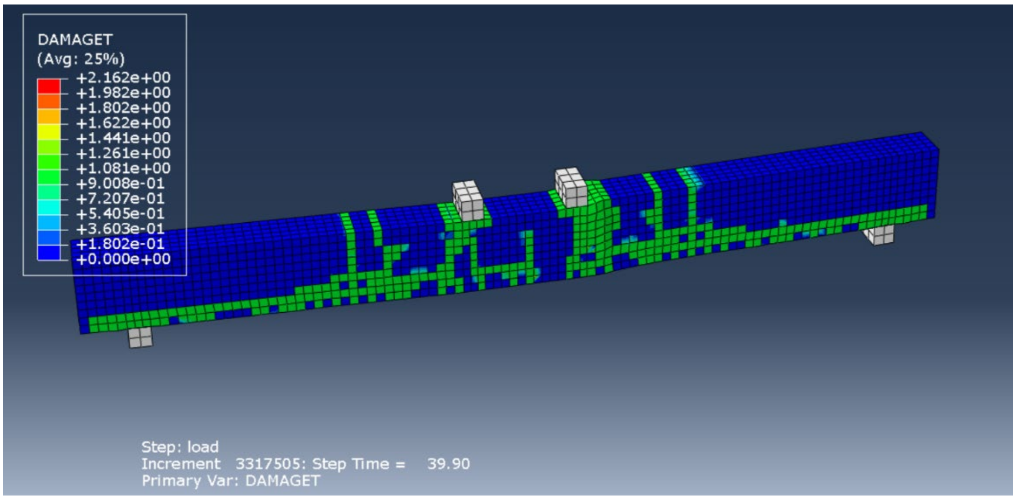

Figure 6 – Flexural failure for control beam

6.References

Bakis, C. E., Ganjehlou, A., Kachlakev, D. I., Schupack, M., Balaguru, P., Gee, D. J., & Kliger, H. S. (2002). Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. *Reported by ACI Committee, 440(2002).*

Ceroni, F., Pecce, M., Matthys, S., & Taerwe, L. (2008). Debonding strength and anchorage devices for reinforced concrete elements strengthened with FRP sheets. *Composites Part B: Engineering*, *39*(3), 429-441.

Ceroni, F. (2010). Experimental performances of RC beams strengthened with FRP materials. *Construction and Building Materials*, *24*(9), 1547-1559.

Darby, A., Ibell, T., & Clarke, J. (2004). TR55 Design guidance for strengthening concrete structures using fibre composite materials. *The Concrete Society.*

Fu, B., Teng, J. G., Chen, J. F., Chen, G. M., & Guo, Y. C. (2016). Concrete cover separation in FRP-plated RC beams: mitigation using FRP U-jackets. *Journal of Composites for Construction*, *21*(2), 04016077.

Grelle, S. V., & Sneed, L. H. (2013). Review of anchorage systems for externally bonded FRP laminates. *International Journal of Concrete Structures and Materials*, *7*(1), 17-33.

Kishi, N., Zhang, G., & Mikami, H. (2005). Numerical cracking and debonding analysis of RC beams reinforced with FRP sheet. *Journal of Composites for Construction*, *9*(6), 507-514.

Kalfat, R., Al-Mahaidi, R., & Smith, S. T. (2011). Anchorage devices used to improve the performance of reinforced concrete beams retrofitted with FRP composites: State-of-the-art review. *Journal of Composites for Construction*, *17*(1), 14-33.

Kalfat, R., Gadd, J., Al-Mahaidi, R., & Smith, S. T. (2018). An efficiency framework for anchorage devices used to enhance the performance of FRP strengthened RC members. *Construction and Building Materials*, *191*, 354-375.

Ibrahim, A. M., & Mahmood, M. S. (2009). Finite element modeling of reinforced concrete beams strengthened with FRP laminates. *European Journal of Scientific Research*, *30*(4), 526-541.

Obaidat, Y. T., Heyden, S., & Dahlblom, O. (2010). The effect of CFRP and CFRP/concrete interface models when modelling retrofitted RC beams with FEM. *Composite Structures*, *92*(6), 1391-1398.

Wang, S., Han, X., & Ji, J. F. (2009). Application of ABAQUS/Explicit in reinforced concrete structures. *Science technology and engineering*, *9*(16), 4688-4692.

Wu, Z., & Niu, H. (2005). Numerical analysis of debonding mechanisms in FRP-strengthened RC beam. *Computer-Aided Civil and Infrastructure Engineering*, *20*, 354-368.