MODELLING CONFINED ZONE EFFECT IN REINFORCED CONCRETE CORBEL STRENGTHENED BY CFRP

Veselin Stankov[1], Ivelina Ivanova[2], Jules Assih[2], Dimitar Dontchev[1]

[1]Department of Applied Mechanics
University of Chemical Technology and Metallurgy
8 Kliment Ohridski Blvd., Sofia 1797, Bulgaria,
stankov_veselin@uctm.edu (V.S); dontchev@uctm.edu (D.D)
[2]Université de Reims Champagne-Ardenne
Institut de Thermique, Mécanique, Matériaux (ITheMM, UR 7548)
51100 Reims, France, ivelina.ivanova@univ-reims.fr (I.I);
jules.assih@univ-reims.fr (J.A)

Received 27 August 2025
Accepted 16 September 2025
DOI: 10.59957/jctm.v60.i6.2025.10

ABSTRACT

Confined zone effect, which is primarily observed in reinforced concrete (RC) columns subjected to compression, is crucial for the load-bearing capacity of (RC) structures. This occurs when, despite an increase in the load, the resulting deformations are nearly zero. The same effect can be observed in structures strengthened by different types of fabrics (carbon, glass, Kevlar, etc.). It is well known that experimental studies are a high-resources and time-consuming process. Therefore, a combination of experimental study and non-linear finite element (FE) simulation strategy is considered. The structure investigated in this paper is an RC corbel strengthened by bonding carbon fibre reinforced polymer (CFRP). Two RC corbel structures were developed, one with strengthening by three layers of CFRP and one without strengthening. The experimental results were used to validate the FE simulation. The model was successfully validated and provides opportunities for future parametric investigations. The aim of this study is to model he confined zone effect in reinforced concrete corbels strengthened by CFRP. Modelling confined zone effect is a significant challenge for engineers. This study shows a new approach to FE simulation. The resulting model successfully simulates the mechanical behaviour of the structure.

Keywords: reinforced concrete, corbel, CFRP, Cohesive Zone Model, Finite Elements, strengthening.

INTRODUCTION

The reinforced concrete corbel is a structural element very often used in the construction of manufactory, residential buildings, and bridges. These structures are subjected at the same time to compression, tension, bending, shear, and dynamic loading. The load-bearing capacity of construction could be reduced by an aggressive environment, excessive load, and fatigue. In addition, changing the design code or the category of use of the construction will bring those structures dangerous for people. One solution is to strengthen these structures. CFRP composites offer high tensile strength, lightweight, and ease of application. Understanding the mechanical behaviour of reinforced concrete structures strengthened by composite materials is crucial for structural engineers because a good strengthening method leads to a great load-bearing capacity and cost efficiency.

The researchers face the problem of the high dimension of the reinforced concrete structural element. That means that they need a big laboratory with heavy machines to reproduce the real mechanical behaviour of the considered structures. The experimental study of this structure is time and resource-consuming process. Therefore, it is recommended the use of (FE) model validated by experimental investigation [1]. Working on strengthening of reinforced concrete structures is a resources-consuming process [1 - 5]. Choosing the proper modelling strategy for strengthening in FE simulation is crucial for a coherent result. Conventional FE methods often struggle to capture the debonding and delamination phenomena that can occur at the interface between the CFRP and the concrete surface. The failure mode significantly influences the overall performance of the strengthened structure and must be accurately modelled. The Cohesive Zone Model (CZM) appears as a powerful technique for simulating debonding and delamination in materials. The traction-separation laws can effectively represent the initiation and propagation of cracks and debonding. This paper aims to develop and validate an FE simulation of CFRP-strengthened RC corbels. The choice of a proper model strategy is crucial to FE modelling. A FE model will be developed and validated against experimental data. The result of this research will provide a valuable computer model for future parametric investigations.

EXPERIMENTAL

Finite elements model development

Constitutive materials properties

Concrete

The FE software provides different models of behaviour of concrete, such as "Smeared crack concrete", "Brittle crack concrete", and "Concrete damaged Plasticity" [6]. In the present study "Concrete damaged Plasticity" (CDP) model was chosen because this model can successfully represent the inelastic mechanical behaviour both in tension and compression. In addition, this model includes the damage characteristics in tension and compression. The CDP model was proposed by Lubliner [7] and later extended by Lee and Fenves [8] for cyclic loading. The constitutive law of mechanical behaviour is as presented in the Eq. (1):

$$\sigma = (1 - d)E_0(\varepsilon - \widetilde{\varepsilon^{pl}}) \quad (1)$$

where: ε- plastic deformation, $\widetilde{\varepsilon^{pl}}$ - equivalent plastic strain, d - damage scalar variable, E_0- is the undamaged modulus.

The damage scalar variable - d, describes the evolution of Young's modulus when Hooke's law is no longer valid (after the elastic limit) and takes values from zero (when the material is undamaged) to 1 (when the material is totally damaged). Based on the research of Stankov [4], the identification of the main parameters of the model was done using the models proposed by Alfarah et al. [9] and Hordijk [10]. A comparative analysis was made by Stankov [4] from different CDP models, and the most suitable model was chosen - the model described by Alfarah et al. [9]. Also, one of the reasons to choose those models is that they consider the finite element dimensions.

- Mechanical behaviour under compression

Fig. 1 presents the strain-stress curve obtained from the CDP model compared with experimental data. The strain-stress curve in compression of the CDP model is divided into three parts. The first linear part (Fig. 1 - blue continuous line) was taken as the prescription given from [11] with value $0.4f_{cm}$. The second part is an increasing exponential function (green continuous line), and the third part is a decreasing exponential function (black continuous line). The experimental data in Fig. 1 are presented by a red dashed line. Must be observed, the experimental data fit very well with the data from the CDP model. The failure mechanism of concrete is described by five parameters as follows:

- dilation (dilatancy angle) angle ψ measured in the p-q plane at high confining pressure - applied value - 36;
- flow potential eccentricity - ϵ, defining the rate at which the hyperbolic flow potential approaches its asymptote - applied value 0.1;
- ratio between the biaxial compressive yield strength fb0and the uniaxial compressive yield strength fc0 - applied value -1.16;
- ratio of the second invariant of the stress on the tensile meridian, defining the form of the yield surface. The following conditions must be met 0.5 < Kc < 1, applied value - 0.66;
- viscosity parameter μ - not applied for explicit analysis.

Fig. 2 depict the compressive behaviour of the concrete section, because of CDP model. It could be notice that the crack propagation is assumed to start after the compressive strength is reached (the damage parameter starts increasing).

- Mechanical behaviour under tension

Based on the model of Alfarah et al., the tension behavior was obtained, and the curves are depicted in Fig. 3 [9].

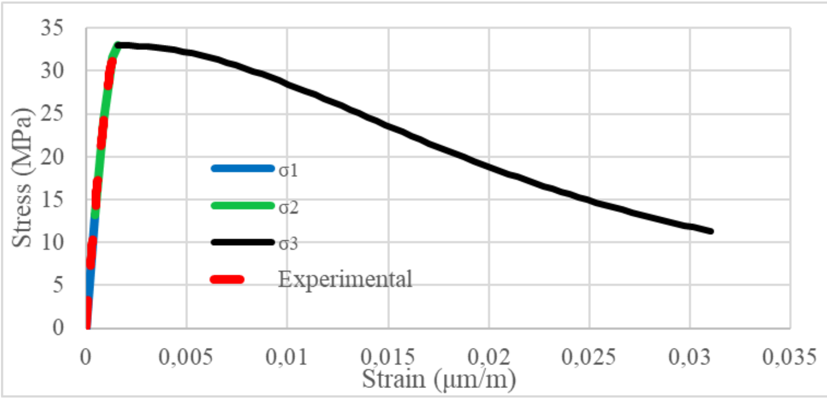

Fig. 1. Compares the experimental result with CDP model.

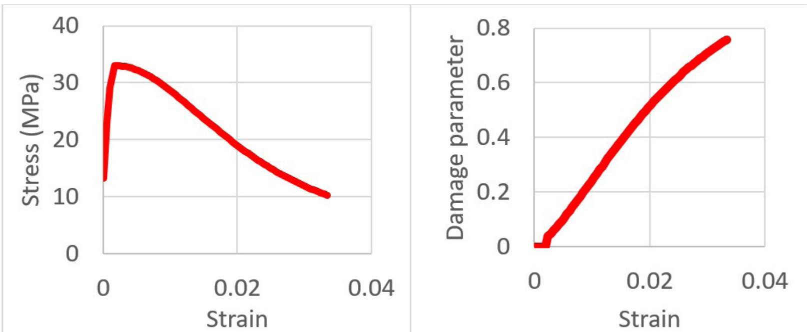

Fig. 2. Compressive behaviour of concrete.

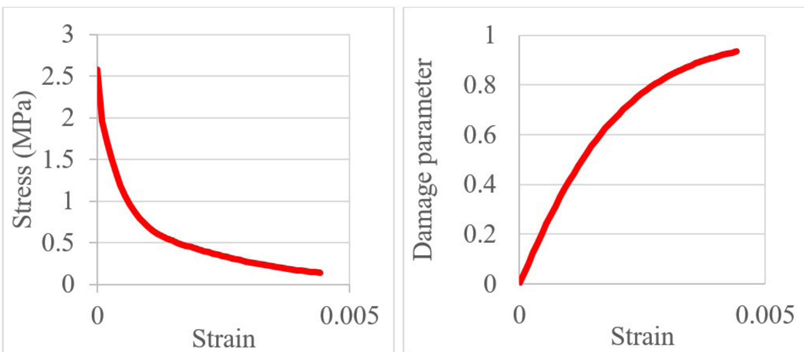

Fig. 3. Tension behaviour of concrete.

Steel reinforcement

Based on the research of Stankov et al. elastic-perfectly plastic model was taken for the steel reinforcement as shown in Fig. 4, taking yield strength of steel [4].

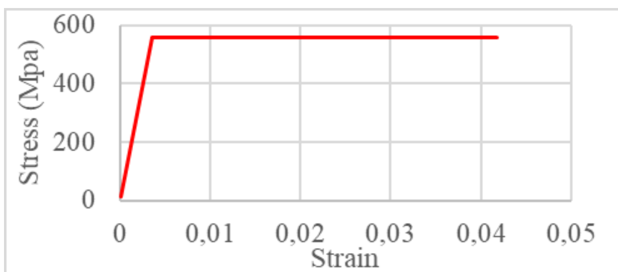

Fig. 4. Elastic-perfectly plastic behaviour of steel reinforcement.

Composite materials

It's difficult to characterize the properties of composite materials experimentally. For that reason, the main properties of CFRP were calculated through

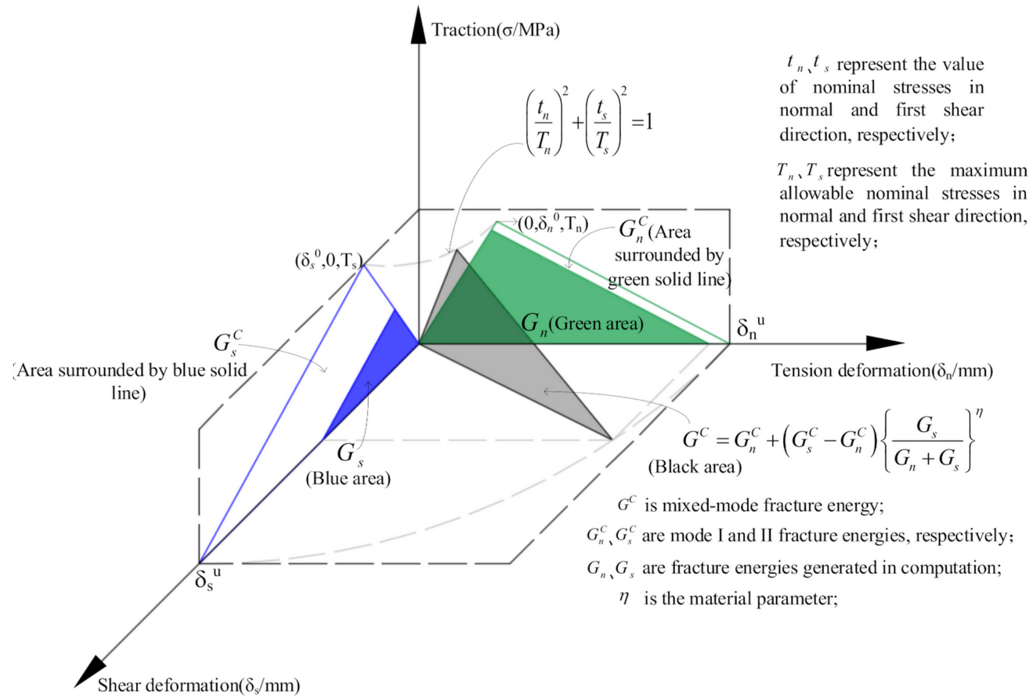

Fig. 5. Mixed-mode response in cohesive elements [6].

Rule of Mixture. Hashin Failure Criteria were used to model the mechanical behaviour of CFRP. Traction-separation law was incorporated [12]. The model has two parallel to the interface components of separation and one perpendicular. The stress-strain curve initially exhibits a linear increase in stress up to the onset of damage. Beyond this point, the structure begins to lose stiffness, resulting in a decrease in stress. The area enclosed by the curve represents the fracture energy of the structure. The onset of damage is determined using the quadratic nominal strain criterion, which states that damage initiates when a quadratic interaction function of the nominal strain ratios reaches a value of one, as described by the following Eq. (2).

$$\left\{\frac{\langle\varepsilon_n\rangle}{\varepsilon_n^0}\right\}^2+\left\{\frac{\varepsilon_s}{\varepsilon_s^0}\right\}^2+\left\{\frac{\varepsilon_t}{\varepsilon_t^0}\right\}^2=1 \tag{2}$$

According to Camanho an effective displacement has to be introduced as it is defined in Eq. (3) [13]:

$$\delta_m=\sqrt{\langle\delta_n\rangle^2+\delta_s^2+\delta_t^2} \tag{3}$$

Fig. 5 depicts the traction-separation response under mixed-mode damage conditions. The vertical axis represents the traction stress acting at the material interface, while the remaining axes quantify the normal and shear separation magnitudes. The unshaded triangular regions on the vertical planes correspond to pure Mode I (normal) and Mode II (shear) failure. Mixed-mode damage is characterized by intermediate planes formed through the interaction of normal and shear separations under applied traction.

The associated fracture energy is dependent on the mode mixity and is evaluated using a power-law fracture criterion. This criterion posits that failure under mixed-mode loading is governed by a nonlinear interaction between the critical energy release rates of the individual fracture modes, expressed through the following power-law relationship (Eq. (4)):

$$\left\{\frac{G_n}{G_n^C}\right\}^\alpha+\left\{\frac{G_s}{G_s^C}\right\}^\alpha+\left\{\frac{G_t}{G_t^C}\right\}^\alpha=1 \tag{4}$$

When $G_s^C=G_t^C$ the critical fracture energies during deformation purely along the first and the second shear, directions are equal, it is recommended to use the Benzeggagh-Kenane fracture criterion (BK) [14]. This criterion is given by Eq. (5):

$$G_n^C+\left(G_s^C-G_n^c\right)\left\{\frac{G_S}{G_T}\right\}^\eta=G^C \tag{5}$$

with $G_S = G_s + G_t, G_T = G_n + G_S$ and η are material parameters.

Model description

The reinforced concrete (RC) corbel specimen is integrated with a column measuring 1.00 m in height and having a cross-sectional dimension of 150 mm × 300 mm. The corbel features a trapezoidal geometry, cantilevered symmetrically on both sides of the column. Each cantilever extends 250 mm horizontally with a width of 150 mm. The overall structural configuration is detailed in Fig. 6.

The column reinforcement comprises four longitudinal steel bars with a diameter of 14 mm, complemented by closed stirrups spaced at 90 mm intervals. The main tensile reinforcement of the corbel consists of 10 mm diameter bars positioned 25 mm below the top surface of the horizontal concrete face. To ensure effective anchorage, two transverse bars of the same diameter were welded at the ends of the main reinforcement.

Strain gauges were affixed to the reinforcement bars to monitor strain during experimental testing. These gauges were shielded against moisture and mechanical damage and connected using a three-wire configuration to minimize signal interference from external equipment. Wooden plates were placed beneath the supports to prevent localized concrete crushing. The test setup involved inverting the specimen relative to its actual service orientation. The applied load on the corbel was generated as a reaction force from a hydraulic jack positioned beneath the column base.

Following the methodology proposed by Ivanova et al., the model incorporates three layers of Carbon Fiber Reinforced Polymer (CFRP), each with a total thickness of 0.566 mm [5]. The primary objective of this study is to evaluate various strategies for modelling the interface behaviour of CFRP sheets in contact with concrete. Three distinct modelling approaches were developed:

- Tie Constraint Approach: CFRP plies are connected using a tie constraint, assuming a perfectly bonded interface.
- Cohesive Contact Interaction: A cohesive behaviour is defined at the interface between the CFRP and the concrete substrate, allowing for progressive debonding.
- Orphan Mesh with Cohesive Elements: Independent (orphan) mesh layers are introduced between the CFRP and concrete section, where additional cohesive finite elements simulate the interface behaviour.

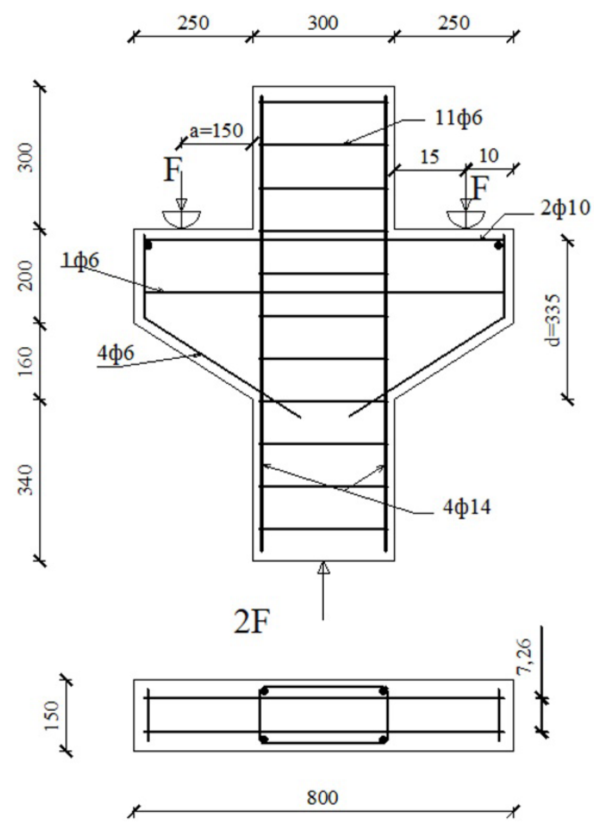

Fig. 6. Dimensions of RC corbel [15].

This comparative modelling framework is intended to assess the influence of different contact definitions on the structural response of CFRP-strengthened elements."

RESULTS AND DISCUSSION

The criteria for validating the FE simulation are as follows:

- Obtaining the load-bearing capacity of the RC Corbel.
- Simulate the mechanical behaviour of the main tension bar of the structure.

The obtained load-bearing capacity of the RC corbel strengthened by three layers of CFRP from experimental investigation was 651 kN. The FE simulation gives 666 kN as a load-bearing simulation, considering that the model is controlled by displacement. The difference between the experimental investigation and FE model is less than 3 % and it can be concluded that the FE

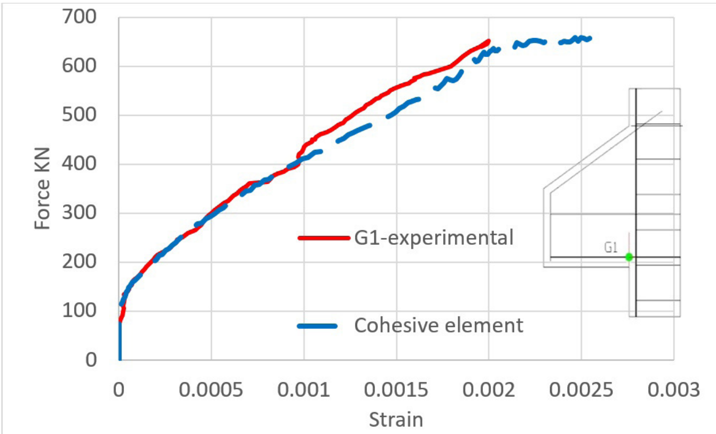

Fig. 7. Comparing experimental data from the strain gauge glued to the main tension bar and FE simulation.

model successfully simulates the load-bearing capacity of the structure.

Fig. 7 depicts the mechanical behaviour obtained by experimental investigation, compared with the FE simulation. It could be noticed that the FE model (blue dashed line) follows the curve obtained by the experimental research, and the confined effect is well represented, which was our goal. Then it could be concluded that the FE model successfully represents the mechanical behaviour of the structure.

CONCLUSIONS

The results show that the mechanical behaviour of the main tensioned bar is well simulated. The considered strategy of modelling led to results close to the experimental investigation taking in account the load-bearing capacity and the mechanical behaviour. The presented study gives an important point for future modelling of RC structures strengthened by composite materials.

Acknowledgment

This research is supported by the Bulgarian Ministry of Education and Science under the National Program "Young Scientists and Postdoctoral Students-2" at University of Chemical Technology and Metallurgy, Sofia, Bulgaria.

Authors' contributions*: V.S.: Computer simulation and model validation; I.I. and J.A.: Experimental investigation; D.D.: Project administration; V.S. and D.D.: Writing and editing; V.S.: Visualization; D.D.: Funding acquisition*

REFERENCES

1. V. Stankov, I. Ivanova, J. Assih, D. Dontchev, Numerical modeling of mechanical behavior of a reinf orced concrete column-short corbel assembly strengthened by bonding a CFRF, IOP Conf. Ser. Mater. Sci. Eng., 1276, 1, 2023, 012023. https://doi.org/10.1088/1757-899x/1276/1/012023
2. V. Stankov, I. Ivanova, J. Assih, D. Dontchev, Numerical simulation of mechanical behavior of reinforced concrete column - short corbel assembly repaired and strengthened by bonding composite materials, IOP Conf. Ser. Mater. Sci. Eng., 1323, 1, 2024, 012008. https://doi.org/10.1088/1757-899X/1323/1/012008
3. A. Yanakieva, G. Nikolova, A. Baltov, Bearing capacity of surface-strengthened concrete beam elements. Parametric analysis, IOP Conf. Ser. Mater. Sci. Eng., 1276, 1, 2023, 012014. https://doi.org/10.1088/1757-899X/1276/1/012014
4. V. Stankov, Étude du comportement mécanique d'un assemblage poteau-console courte en béton armé renforcé ou réparé par collage de matériaux

composites, 2021. Available: http://www.theses.fr/2021REIMS026/document
5. I. Ivanova, J. Assih, D. Dontchev, Influence of anchorage length of composite fabrics and bonded surface on the strengthened short reinforced concrete corbel by bonding CFRF, European Journal of Environmental and Civil Engineering, 24, 12, 2018, 1993-2009. https://doi.org/10.1080/19648189.2018.14983952018
6. M. Smith, Abaqus/Standard User's Manual, Version 6.9. United States: Dassault Systèmes Simulia Corp, 2009.
7. J. Lubliner, J. Oliver, S. Oller, E. Oñate, A plastic-damage model for concrete, Int. J. Solids Struct., 25, 3, 1989, 299-326, https://doi.org/10.1016/0020-7683(89)90050-4
8. J. Lee, G.L. Fenves, Plastic-Damage Model for Cyclic Loading of Concrete Structures, J. Eng. Mech., 124, 8, 1998, 892-900. https://doi.org/10.1061/(ASCE)0733-9399(1998)124:8(892)
9. B. Alfarah, F. López-Almansa, S. Oller, New methodology for calculating damage variables evolution in Plastic Damage Model for RC structures, Eng Struct, 132, 2017, 70-86. https://doi.org/10.1016/j.engstruct.2016.11.022.
10. D.A. Hordijk, Tensile and tensile fatigue behaviour of concrete; experiments, modelling and analyses, Heron, 37, 1, 1992.
11. European Committee for Standardization, "EN 1992-1-1: Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings," Brussel, 2004.
12. Z. Hashin, Failure Criteria for Unidirectional Fiber Composites, J. Appl. Mech., 47, 2, 1980, 329-334. https://doi.org/10.1115/1.3153664
13. P.P. Camanho, Failure criteria for fibre-reinforced polymer composites, 2002.
14. M. Kenane, M.L. Benzeggagh, Mixed-mode delamination fracture toughness of unidirectional glass/epoxy composites under fatigue loading, 1997.
15. I. Ivanova, Comportement mécanique de console courte en béton armé renforcée ou réparée par collage des matériaux composites. Reims, France : Thèse de doctorat, Université de Reims Champagne-Ardenne, 2013.