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Model analysis of carbon fiber reinforcement properties for reinforced concrete beams to resist blast loads

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ABSTRACT

Safety is paramount in Oil & Gas plants, and continuous monitoring and improvements ensure that all measures are taken to protect them. The purpose of this paper is to examine how composite materials can be used to improve the structural reinforcement of concrete beams. Concrete structural beams have been improved in the past by using varying Fiber Reinforced Properties (FRP). It has been investigated how Carbon Fiber Reinforced Properties (CFRP) composites perform under blast loads and how they behave, respond, and perform as reinforcement for reinforced concrete beams. The response of RC beams to blasts was analyzed using a software modelling program called ANSYS that can mimic RC beam properties when reinforced with CFRP in concrete structures. The reason CFRP was chosen was because its properties showed great potential and it is well suited for testing and analysis. As well as absorbing a lot of energy, this material is strong, elastomeric, and alkali-resistant. A numerical analysis and model analysis have been performed with the help of the ANSYS software program. In the experimental results, CFRP was found to increase the flexural and shear strength of RC beams. The RC beams reinforced with CFRP has outperformed RC beam (control beam) in factors such as in Deformation, Equivalent Stress, and Shear Stress by a minimum percentage difference of 0.784% and maximum of 7.09% depending on the layers of CFRP and load applied on the beams in each factor.

1. Introduction

There have been an increasing number of accidents, earthquakes, terrorist attacks, and spills of corrosive gas and liquid that have led to explosions over the past few years [1]. Oil and gas plants have caused numerous off-site disasters, which destroyed critical structures, killed people, contaminated the environment, and damaged critical equipment [2]. Approximately 1100 claims were made in the petroleum and chemical insurance industries between 1993 and 2013 [5]. There have been several reports of hydrocarbon explosions being the most dangerous mishaps. Off-site facilities pose a high risk since most plant operations take place there and hydrocarbons that may ignite or explode are exposed there [5]. The structural and operational integrity of petrochemical plants has been under increased scrutiny after numerous dangerous accidents [6].

A hydrocarbon explosion or pipeline rupture typically results in the total destruction of off-site concrete structures because the beams bend or are not reinforced with blast-resistant reinforcement [5]. Concrete buildings, including storage tanks, utility systems, flares, environmental treatment units, employee and worker quarters, control and communication rooms, and other off-site facilities, are usually supported by reinforced concrete beams to prevent the potential hazards listed above [3,4]. As discovered by Kishore et al. [7], concrete has a low compressive and tensile strength. It is possible for concrete structures to fail due to structural or design flaws, design changes, vibration settlement, overloading, and blast loads. To prevent damage caused by these factors, concrete beams or buildings must be reinforced or upgraded.

The retrofitting and strengthening of reinforced concrete structures can be accomplished through the use of lightweight, durable, and noncorrosive fiber reinforced polymers (FRPs). Reinforcing RC beams with FRPs has become an increasingly common alternative to traditional materials [9]. In addition to being mechanically and

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economically advantageous, carbon fiber reinforced polymer (CFRP) systems enhance reinforced concrete beam strength, as discussed by Sorin et al. [13]. In experiments, CFRP beams outperformed BFRP and standard concrete beams in compressive strength [14].

Carbon fibers resist acids, alkalis, and organic solvents because they do not absorb moisture [15,16,17,18]. In a few experiments, CFRP was used to reinforce damaged reinforced concrete beams, resulting in as much as 95% increase in flexural strength [20,21].

There have been extensive studies on how CFRP could be used to make blast resistant RC beams in public, government, and conventional structures, this concept has not been applied to off-site oil and gas facilities adequately or in a timely way, and this is where the limitation of the study was set. Specifically, the study was undertaken on islands that have off-site structures supporting oil and gas production activities. A new generation of blast resistant design technology has evolved from static to dynamic designs in the oil and gas industry [22], which are safer and more appropriate for normal operations and pre-commissioning conditions that emphasize minimal obstructions to process flow. In most oil and gas plants, the ability to withstand explosions caused by hydrocarbons has not been taken into account during their construction and installation, and their harboring has often been poor or nonexistent [2]. The study proposes designs for RC beams reinforced with CFRP sheets at off-site oil and gas plants with the help of ANSYS software and finite element analysis. Oil and gas plants can benefit from tools such as FE ANSYS when designing blast resistant concrete buildings, as it can produce beam models and provide information. ANSYS simulation environment has been extensively tested and validated by the authors [12,24,25] and other researchers [10,11,23,25,26,27,28,29,30] to model FRP-strengthened structures.

This study adds to the scientific knowledge and addresses the existing gap in the literature in the engineering field on the designing of RC beams at the off-site of oil and gas plants against blast loads. We constructed a three-dimensional model of a reinforced concrete beam arrangement from Neagoe [31] to assist with model validation. A comparison between Neagoe's [31] results and numerical simulation results was conducted prior to modifying the model for further research.

2. Aim & objectives

A finite element method was used to quantify CFRP, a numerically evaluated material for strengthening RC beams in off-site concrete structures in the oil and gas industry, including their strength in flexure and shear, as well as their ability to withstand blast loads, as external reinforcement materials. This goal was achieved by establishing the following objectives:

- Under blast loads, assess the dynamic behavior, response, and performance of RC beams without CFRP reinforcement.
- Perform a dynamic analysis of RC beams reinforced with CFRP under impact/dynamic loads to determine their performance (shear and flexion capacity).
- Identify and create 3D models of reinforced concrete beams reinforced with CFRP that will be used in off-site concrete structures to withstand hydrocarbon explosions at oil and gas plants.

3. Methods

3.1. Design and setting of the study

In this study, finite element modeling was based upon experimental data from Neagoe [31] at Catalonia's Polytechnic University. Five RC beams were modeled using ANSYS software to generate 3D finite elements (FE) in accordance with Neagoe's previous laboratory work (33). Four-point loading was used to test all five 3D FEs, as it was in Neagoe's laboratory experiments [31]. (Refer with: Fig. 1). This study aimed to strengthen concrete structures at oil and gas plants off-site by using simulation results. Neagoe's laboratory experiments found that each beam measured exactly 200 mm wide, 400 mm tall, and 4500 mm long, with a clear span of 4000 mm. In this case, the shear span-to-depth ratio was at least six, which indicates sufficient continuous mobility for the RC beam to fail only after it reaches the required deflection. Two 12 mm steel bars were used at the top and bottom of each RC beam for flexural reinforcement, and the shear reinforcement was the same. Stirrups of 12 mm steel were positioned every 200 mm to provide shear reinforcement. The structural design was made to be sufficiently robust to withstand flexure without additional reinforcement. A CFRP layer was applied to the outside of the RC beams to reinforce them. There was no CFRP application on one beam (A1) for external reinforcement. CFRP sheets were used to reinforce four beams (C1, C2, C3, and C4): the first two beams (C1 and C3) were strengthened with single CFRP sheets and the other two beams (C2 and C4) were strengthened with double CFRP sheets (refer with: Table 1). There were four beams in the sample; C1, C2, C3, and C4. Each beam was reinforced with the same amount of CFRP reinforcement (MBrace Composite CFRP Laminates LM) with 69–70 percent fiber volume, 158GPa modulus of elasticity, 2200 N/mm2 ultimate tensile strength, and density of 1.6 g per cubic centimeter. A 15-meter-long coil of sheets had a diameter of 50 mm and a thickness of 1.4 mm. The same adhesive material was used to bond these sheets to the tension face of the RC beams (epoxy primer (MBrace Resin 50) and a two-part epoxy resin (MBrace laminate adhesive: concresive 1460) on 3200 mm of RC beams. The concrete used for the foundation was C35/45, and the steel used was B500 S, which was high-strength in nature. In this study, five CFRP laminated RC beams with varying numbers of CFRP laminates were subjected to loading schemes I and II to assess their behaviors (refer with: Fig. 1). Both procedures were identical except for the loading force-distance.

3.2. Finite element modelling

The dynamic loads were applied incrementally to five 3D FEs using ANSYS 2020 Design Modeler (see Fig. 1). For beam A1, concrete and steel were combined, meshing was used, and boundary conditions were applied, while for beams C1, C2, C3, and C4, concrete and steel reinforcement were combined, meshing was used, and boundary or loading conditions were applied to a CFRP system. Each of these components was adequately modeled so that their distinct characteristics could be captured in the study. For the modeling of concrete mechanical properties, SOLID65 elements were used in ANSYS software [32]; Solid45 elements (ET command 1,45) for steel rebars and stirrups [8]; SHELL99 elements for CFRP laminates [25,33]; and INTER205 cohesive elements for epoxy resins and epoxy primers [34].

3.3. Convergence and failure criteria

By applying the dynamic load gradually till failure, in ANSYS software, we were able to investigate the FE models we created by dividing the length of the beam into three segments and applying load steps and sub-steps commands at two sites (refer to: Fig. 1). The responses and flexural behavior of the five 3D FE are analyzed through the calculation of total deformation, directional deformation, equivalent stresses (von Mises stresses), shear stresses, and Vector Principal Elastic Strains. Deformation: Beams were

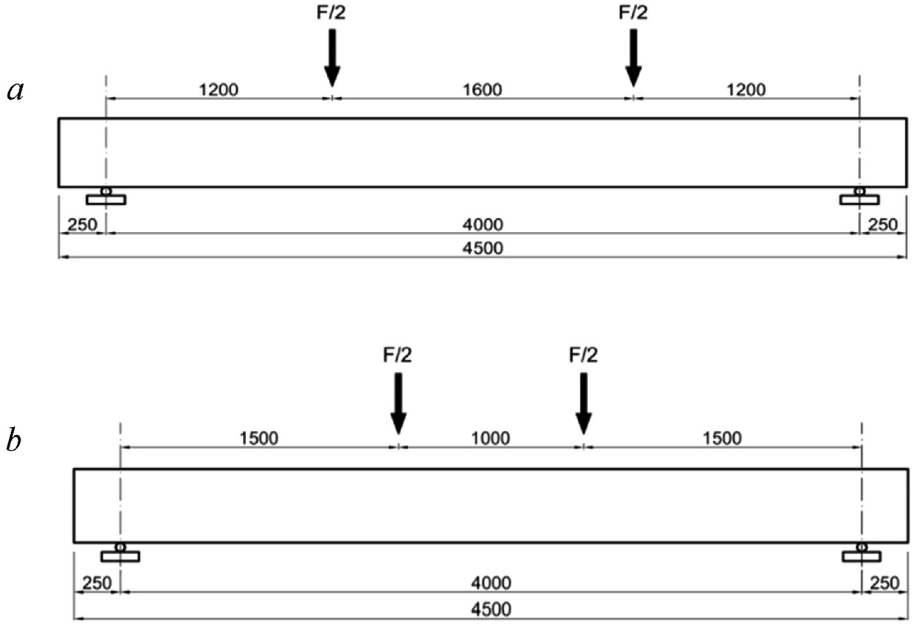

Fig. 1. (a) Loading Scheme I, (b) Loading Scheme II.

Table 1
Characteristics of the RC beams.

RC Beam	Load scheme	No. of Sheets	FRP Area (mm^2)	Steel % in tension (Ps*10^{-2})	FRP % in tension (PFRP*10^{-2})	Equivalent reinforcement % (Peq*10^{-2})
A1	I	0	0	0.280	–	0.280
C1	I	1	70	0.280	0.087	0.349
C2	I	2	140	0.280	0.175	0.697
C3	II	1	70	0.280	0.087	0.349
C4	II	2	140	0.280	0.175	0.697

subjected to deformation analysis to determine if there was sufficient displacement to cause a reaction [19].

Equivalent stresses, von Mises stresses and failure mode: Equivalent stress analysis is a useful tool for determining if a material's von Mises stress under load or application of force equals or exceeds the material's yield limit in simple tension when modeled for RC beams. Shear stresses: When RC beams fail, shear stress analysis can help determine why. A beam's shear strength is determined by its shear stress level, so it is important when designing and analyzing concrete buildings [35].

Vector principal elastic strain: According to the maximum principal theory, structures fail when their maximum principal stress value exceeds their limiting value. A beam during construction must not be subject to a principal stress that is greater than the failure stress to avoid a failure state [36].

3.4. Model validation

The validity and accuracy of the simulation were evaluated using Neagoe's laboratory investigation [31]. To validate the model, Neagoe's [31] findings were compared to the numerical simulation results. For the five beams, the 3D FE models were identical to those Neagoe had previously developed in the laboratory (33).

4. Results

The methodology section details three RC beam scenarios. A reference or control beam was the first scenario, and it was not strengthened. CFRP was used in one layer and two layers in the remaining cases. A variety of factors were investigated regarding the behaviors and reactions of these beams, including deformation behavior, equivalent stresses (von Mises stresses), shear stresses, and Vector Principal Elastic Strain. These were the results:

4.1. Deformation

A summary of total deformation in the five RC beams can be seen in Table 2. A comparison is also made between the findings and Neagoe's [31] experiments.

Table 2 summarizes how externally reinforced beams outperformed control beams. Further, double CFRP reinforced beams performed better in terms of strength and stiffness than single CFRP reinforced beams. Under loading schemes I and II, a double reinforced beam C2 and C4 display the same overall deformation or displacement differences. The difference between beams C2 and C4 is 2.435 percent when compared to beam A1. C1, C3, and CFRP retrofitted beams exhibit varying outcomes. Different loading techniques were used, resulting in various types of premature failures, which contributed to the disparity in performance. This study confirms Neagoe's laboratory findings [31], which showed that using CFRP sheets to reinforce RC beams increases their loading capacity, and that using two sheets further improves the loading capacity by preventing deformations, plastic joints, yielding, or flexural failures.

4.2. Equivalent stresses, von Misses and failure mode

A summary of the von Mises stress distribution within the five RC beams is presented below in Table 3. Moreover, Neagoe's exper-

Table 2
Summary of total deformation behavior of the five RC beams.

Beams	Loading Scheme	No. of CFRP sheets	Maximum deformation (m)	Comparison with control beam A1 (%)
A1	I	0	0.017573	–
C1	I	1	0.017351	1.26
C2	I	2	0.017145	2.435
C3	II	1	0.017225	1.98
C4	II	2	0.017145	2.435

Table 3
Summary of von Misses distribution among the five RC beams.

Beams	Loading Scheme	No. of CFRP sheets	Maximum von Mises stress (Pa)	Comparison with control beam A1 (%)
A1	I	0	5.0352×10^8	–
C1	I	1	4.996×10^8	0.784
C2	I	2	4.957×10^8	1.55
C3	II	1	4.678×10^8	7.09
C4	II	2	4.950×10^8	1.692

imental study [31] was compared to the findings of the current study.

Von Mises stress is higher in unreinforced beams than in reinforced beams. During beam A1, the steel bar's stress increases, reaching its yielding point, when a large portion of the additional von Mises stress is absorbed by massive deformation, resulting in a lower concrete strain growth. Due to the distribution of tensile stresses among reinforcement plates and steel bars in reinforced beams, stresses carried by steel bars are generally lower than the steel's yield strength. Concrete strains are higher in reinforced beams than they are in control beams. This corresponds to Neagoe's [31] observation that when CFRP sheets are used more frequently, the stress is shared between the sheets and steel bars, thereby decreasing steel stress. This reduces the von Mises stress maximum value because the steel yield point is not reached.

4.3. Shear stresses

The summary of shear stress distribution among the five RC beams is depicted in Table 4.

Without reinforcement, tension builds in the steel bars until they reach their yielding point. Concrete's compressive strain rise is lower due to steel deformation absorbing a considerable proportion of it. In reinforced beams, steel bars and reinforcing plates are subjected to the same tensile stress. Due to this, steel's yield strength may not be achieved, because of the lower stress on steel bars. Double CFRP reinforcements can therefore withstand greater shear stresses than single CFRP reinforcements. Differences in the loading procedures between beams C1 and C2 are the cause of the variances between those beams. According to Neagoe [31], when the number of CFRP sheets increases, a significant portion of stress is shared between the sheets and steel bars, resulting in lower steel stress, in line with these results.

4.4. Summary of principal stress analysis

The von Mises calculations showed that the FRP plates and steel bars would share main stresses when reinforced with single reinforcement (beams C1 and C3). With more sheets shared between the steel bars (Beams C2 and C4), major stresses were reduced as they were shared amongst them. The principal stress of a double reinforced structure is low, below the strength limits of components, beams, and structures. The CFRP reinforcement absorbs a considerable share of the principal stresses, keeping them below the material's yield strength. Increasing the number of CFRP sheets inhibits steel bars from experiencing major stresses, as Neagoe found [31] in his experiments.

4.5. Application/benefits of the numerical analysis

- Numerical analysis demonstrates the feasibility of constructing blast-resistant RC beams on the basis of FE models without the need for test results to strengthen concrete structures.
- A large concrete structure can be examined through the use of various finite element models, blast pressure–time accounts, and observations of its reaction following collapse by using this simulation as a pre- or post-analysis.
- A thorough analysis of the mechanical behavior of various components added to concrete is presented in this study. It helps improve the mechanical performance, fracture energy, and ductility of concrete.
- By using numerical simulations, structures affected by gas explosions or other blast loading scenarios can be assessed for damage caused by pressure-impulse curves.
- Using this research, structural engineers are able to design structural members that are appropriate for the particular structure.

Table 4
Summary of Shear Stresses analysis.

Beams	Loading Scheme	No. of CFRP sheets	Maximum shear stress (Pa)	Comparison with control beam A1 (%)
A1	I	0	2.0917×10^7	–
C1	I	1	2.0768×10^7	0.712
C2	I	2	2.0694×10^7	1.07
C3	II	1	1.9981×10^7	4.47
C4	II	2	2.0694×10^7	1.07

5. Conclusion

To achieve the study's objectives, five RC beams were evaluated: one control beam, two with single CFRP laminates attached, and two with double CFRP laminates. In the investigation, the strength of the FRP system was evaluated primarily through the analysis of the final behavior. These conclusions can be drawn for each study objective based on the above-mentioned simulated results:

5.1. Research objective 1

An evaluation of RC beams with no CFRP reinforcement under blast loads was conducted in this numerical study to determine their dynamic behavior, responsiveness, and properties. Beam A1 (with no external reinforcement) showed the greatest total deformation, von Mises stress, shear stress, and principal stress in this study. Due to the pressure created by the applied force, more stress is released into the steel bars, which increases until the steel bars are unable to take on any more stress (their yield point). RC beam ties take on more stress when there is no CFRP reinforcement, so the highest values are the result.

5.2. Research objective 2

RC beams reinforced with CFRP were subject to impact/dynamic loads to examine their dynamic response and performance (shear and flexural capacities). The CFRP sheets were used to reinforce beams C1, C2, C3, and C4: two with a single reinforcement (C1 and C3), and two with a double reinforcement (C2 and C4). With respect to total deformation, von Mises stress, shear stress, and principal stress, beams with two CFRP sheets performed relatively well. The degree of damage to RC beams when subjected to blast loads is reduced by single reinforcement. A second layer of reinforcement further reduced the damage. This scenario reduces steel's ability to yield due to the distribution of stress across CFRP sheets and steel bars. Utilizing lamenting results in a more uniform distribution of stress. By increasing the number of CFRP sheets from one to two, the amount of stress in the steel bars was further reduced, resulting in the steel bars not yielding under maximum tension.

5.3. Research objective 3

Thirdly, the study sought to develop 3D models of RC beams reinforced with CFRP for off-site concrete structures at oil and gas plants that would withstand hydrocarbon explosions and other blast loads. Based on the findings of the study, 3D models of RC beams reinforced with two layers of CFRP could be used to strengthen concrete structures off-site at oil and gas facilities. A beam reinforced with two layers of CFRP requires more explosive mass to cause damage to the RC beam compared to RC beam with no CFR layers based on the modeling outcomes shown in this paper. Adhesives are crucial when it comes to preventing failure modes.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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