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Evaluation of Hybrid Fiber Reinforced Polymer Reinforcement in Unidirectional Concrete Slabs

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Abstract- **Fiber-reinforced polymer (FRP) composites are being increasingly used in civil engineering due to their high strength-to-weight ratio, sturdiness, and corrosion resistance. Several studies have been conducted on the mechanical characteristics, robustness, and uses of FRP composites in civil engineering. The current study aims to develop better recommendations for a more balanced design by evaluating the analytical and experimental behavior of hybrid fiber reinforced polymer reinforcement (HFRP) reinforcement in unidirectional concrete slabs using more precise modeling and analysis. The study investigates the bending behavior and mechanical characteristics of slabs of unidirectional reinforced concrete that have been reinforced with steel and HFRP, respectively. The density, tensile strength, elastic modulus, linear thermal expansion coefficient, and bond strength of the employed materials are studied. The bending behavior of reinforced concrete slabs with HFRP and steel reinforcement is experimentally investigated under two-point static loading circumstances. The study contributes to developing a generic analytical method that can predict the predicted operational load deflection of FRP reinforced parts with reasonable accuracy.**

Keywords: **Fiber-reinforced polymer (FRP) composites, Polymer matrix, Glass fibers, Carbon fibers.**

INTRODUCTION

Fiber-reinforced polymer (FRP) composites are substances made of a polymer matrix that has been strengthened with fibres. These fibres, which often consist of glass, carbon, aramid, or basalt, provide the composite material its strength and rigidity [1]. Typically, thermosetting resins like epoxy, polyester, or vinyl ester are used to create the polymer matrix. Numerous industries, including those in the aerospace, automotive, marine, civil engineering, and sports equipment, are using these composites more frequently. In comparison to conventional materials like metals and concrete, they have a high strength-to-weight ratio, are resistant to corrosion and fatigue, and are flexible in terms of design [2]. FRP composites come in a variety of forms, including woven [5], unidirectional [3], and bidirectional [4]. Bidirectional composites feature fibres that are orientated in two directions as opposed to unidirectional composites, which only contain fibres that face one direction [4]. Fibres in woven composites are interwoven, improving both flexibility and impact resistance [5]. A variety of techniques, including manual lay-up, filament winding, pultrusion, resin infusion, and compression moulding, can be used to create FRP composites. The intended qualities, the part's complexity, and the volume of production all influence the manufacturing method selection. Because of their outstanding corrosion resistance, high tensile strength to weight ratio, and good non-magnetic qualities, FRP reinforcement in concrete structures has seen a sharp surge in application in recent years.

Figure 1 Four Different Forms of FRP Composites [6]

FRP materials outperform more traditional building materials like wood, steel, and reinforced concrete in terms of stability, stiffness, strength, and longevity. This is due to their superior quality of construction. Due to the lower modulus of elasticity of FRP, concrete components reinforced with FRP bars show more deflection and crack breadth than those reinforced with steel. As a result, the design of such members is frequently constrained by serviceability limit states, making it very advantageous to develop a generic analytical method that can predict the predicted operational load deflection of FRP reinforced parts with reasonable accuracy. Since FRP bars must be reinforced with reinforcement because they have different mechanical properties from steel bars, such as a lower modulus of elasticity and a higher tensile strength combined with an elastic brittle stress-strain relationship, the analytical procedure created for designing reinforced concrete structures with steel bars must also be used with FRP. The primary goal of the current study is to develop better recommendations for a more balanced design by evaluating the analytical and experimental behaviour of hybrid fibre reinforced polymer reinforcement (HFRP) reinforcement in unidirectional concrete slabs using more precise modelling and analysis.

Due to its high strength-to-weight ratio, sturdiness, and corrosion resistance, fiber-reinforced polymer (FRP) composites are increasingly being used in the field of civil engineering. Researchers have recently done a large number of studies on the mechanical characteristics, robustness, and uses of FRP composites in civil engineering. A study on the mechanical characteristics and toughness of flax/glass fibre bio-hybrid FRP composite laminates was done by Liu et al. in 2022 [6]. They discovered that the mechanical characteristics and durability of the FRP composites were enhanced by the hybridization of flax and glass fibres. A review of the effects of fatigue, numerous, and recurrent low-velocity impacts on FRP composites was done by Sadighi and Alderliesten in 2022 [7]. They discovered that the complex fatigue behaviour of FRP composites under impact loading called for additional study. The current state and potential uses of recyclable LRS FRP composites for engineering constructions were examined by Ye et al. in 2021 [8]. They discovered that the usage of recyclable LRS FRP composites could lessen the negative effects of building on the environment and improve the built environment's sustainability. Siddika et al.'s review of fiber-reinforced polymer composites' use in reinforcing reinforced concrete beams was published in 2019 [9]. They discovered that adding FRP composites to reinforced concrete beams improved their flexural and shear capacities. The usage of FRP composites in the bridge sector was examined by Ali et al. (2021) [10]. They discovered that FRP composites were successful in boosting bridges' durability and load carrying capacity. The mechanical behaviour of natural fiber-reinforced polymer composites and its applications were reviewed by Jariwala and Jain (2019) [11]. Natural fiber-reinforced polymer composites were discovered to have good mechanical characteristics and to be environmentally benign. Yumnam et al. (2021) [12] reviewed active infrared thermography's use in the inspection of concrete structures that were externally reinforced with FRP composites. For the inspection of FRP-reinforced concrete structures, they discovered that active infrared thermography was a promising non-destructive testing technique. The most recent research on prefabricated FRP composite jackets for structural restoration was evaluated by Mohammed et al. (2020) [13]. They discovered that recovering the structural integrity of damaged structures was possible with the help of prefabricated FRP composite jackets.

The current study's goal is to look into the bending behaviour and mechanical characteristics of slabs of unidirectional reinforced concrete that have been reinforced with steel and HFRP, respectively. The study seeks to investigate the density, tensile strength, elastic modulus, linear thermal expansion coefficient, and bond strength of the employed materials. Under two-point static loading circumstances, the bending behaviour of reinforced concrete slabs with HFRP and steel reinforcement is experimentally investigated. Additionally, bending behaviour of reinforced concrete slabs with HFRP and conventional reinforcement under the same loading conditions is investigated using finite element modelling with ANSYS 15.1. The work provides updated theoretical equations for unidirectional HFRP reinforced concrete slab bending capacity, deflection, and crack width under static two-point loading circumstances. A resistance-based model for the bending potential of unidirectional HFRP reinforced concrete slabs is created using Monte Carlo simulations with randomly generated data sets.

I.METHODOLOGY

The finite element method (FEM) is a numerical approach for estimating structural analysis solutions. Although utilised most frequently in the aerospace, biomechanical, and automotive industries, it is extremely helpful in computing structural analysis problems in a wide range of building industries. In order to make the analysis simpler, this strategy divides the entire complicated structure into simpler or smaller components. The structural performance of the unidirectional slab used in the current investigation is therefore described using FEM.

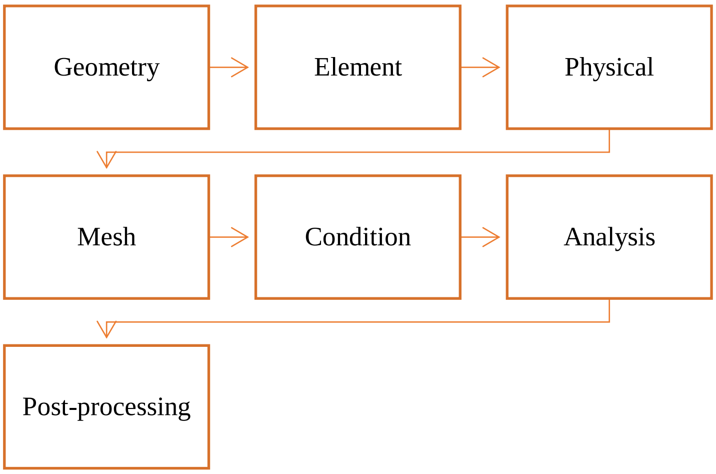

Figure 2 Modelling process of Finite Element Analysis

The full-size unidirectional plate is replicated by the finite element model used in this investigation. With variable reinforcement, reinforcement ratio, concrete quality, and slab thickness, a total of 18 single-sided slabs were modelled. The plates have a 600 mm width, a 2400 mm span, and two thicknesses of 100 mm and 120 mm. They are rectangular in shape. Finite Element Analysis (FEA) is used to construct 18 full-size plates, which are then put under two point loads to simulate the circumstances of the experiment. The only use of roller and pin supports is support location.

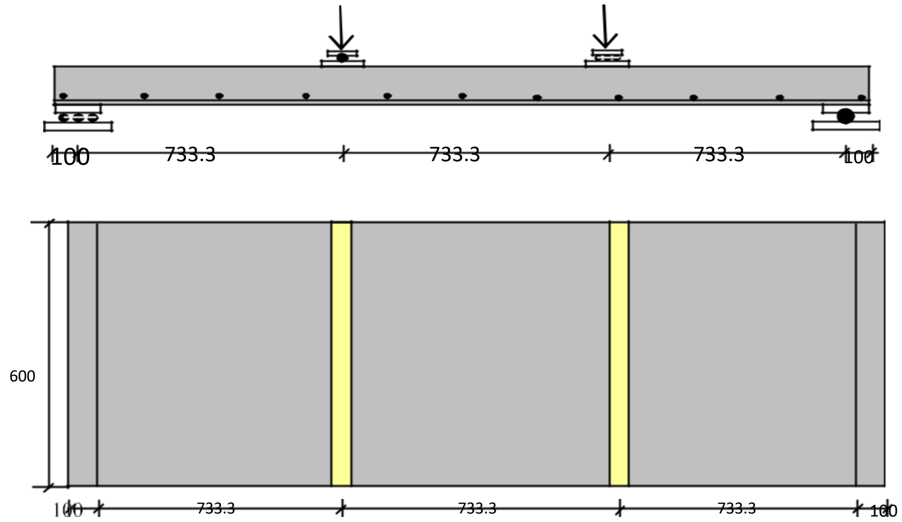

Figure 3 Model of one-sided plate with loading device (all dimensions are in mm)

To numerically assess the performance of a one-sided slab, a three-dimensional nonlinear finite element analysis is used. Both conventional and HFRP reinforced plates are subject to the same loads and supports. The slab has 8 nodes and 3 degrees of freedom (DOF) at each node and is created as a three-dimensional brick element. This element's treatment of nonlinear features sets it apart from others. This element has greater stress capabilities, considerable deflection, and stress hardening. There are two limitations on this element: neither elements with zero volume nor elements with less than eight nodes are permitted.

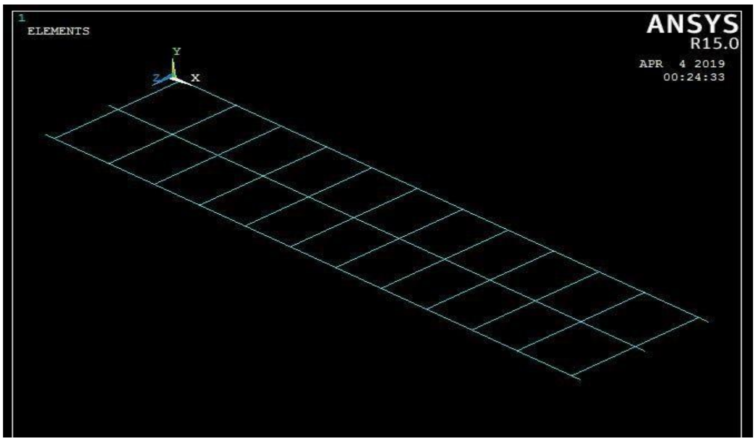

Figure 4 Model HFRP reinforcement

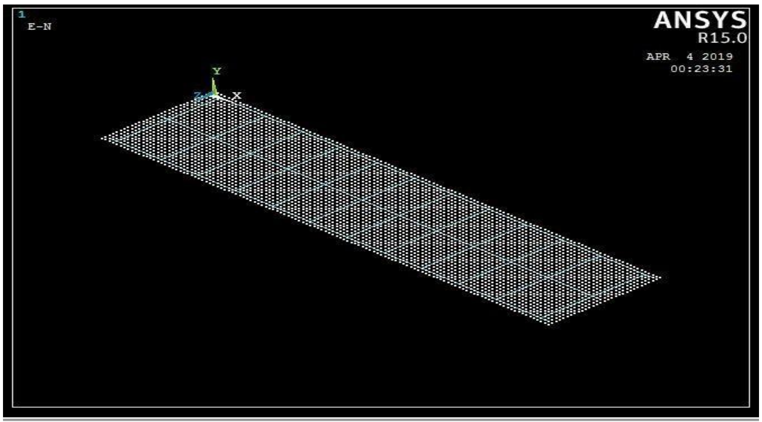

Figure 5 Construction of Link 180 elements

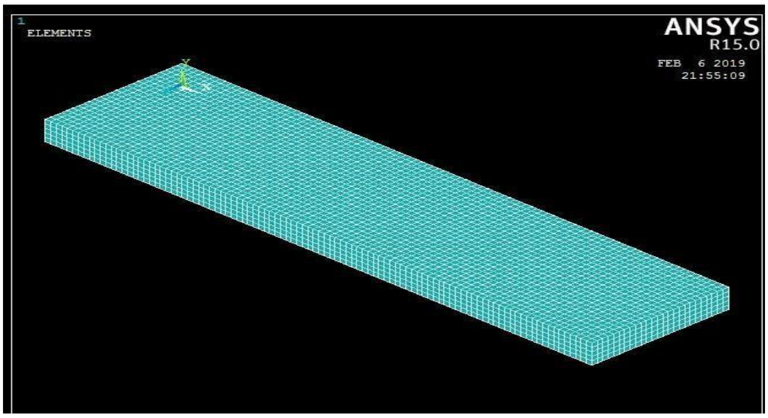

Figure 6 Modeling of the slab

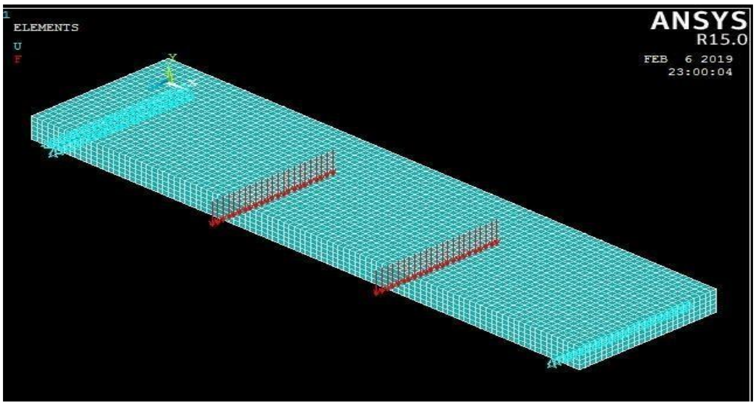

Figure 7 Loading and Support Position

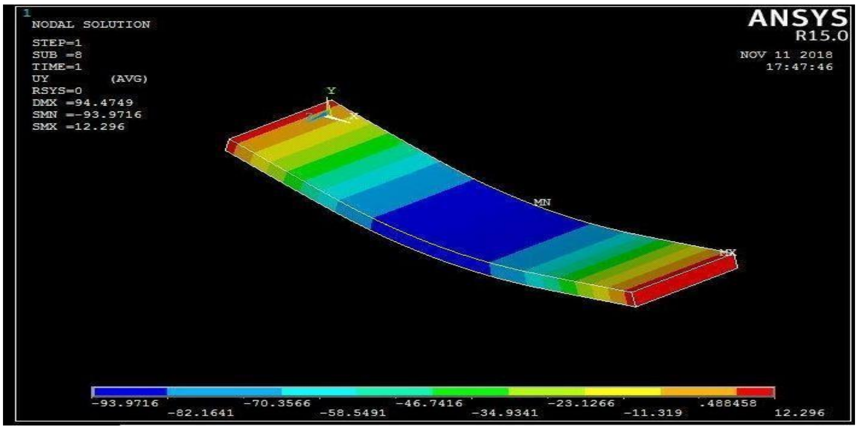

Figure 6 Curved profile of HFRP M1H1D1 sheet

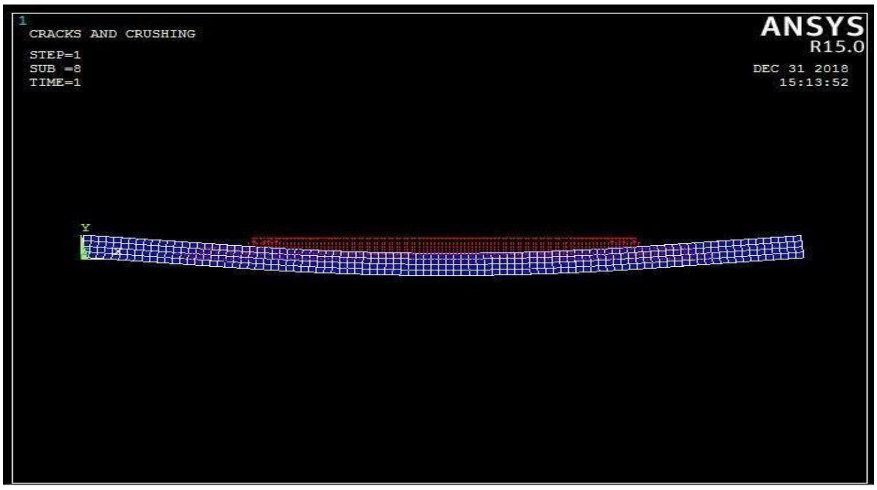

Figure 9 Crack pattern of HFRPm1h1d1stone slab

In order to create a trustworthy and computationally effective finite element model of a unidirectional slab under two-point loading conditions, a static nonlinear analysis was carried out using the finite element programme ANSYS 15. The software's applicability was evaluated for comparison by contrasting it with experimental findings. The experimental deflection is 1.03 to 1.37 times greater than the ANSYS deflection, which illustrates that there is little difference between the two methods' outputs. According to the experimental behaviour, load deflection charts illustrating the finite element modelling (FEM) behaviour are displayed. However, in both the linear and nonlinear categories, the finite element models exhibit a lower deflection than the experimental findings. The high stiffness of the meshing approach is caused by this small finite element. The outcomes show that the bond slip and strain hardening effect is in superb agreement with the outcomes of the experiments.

The load and resistance of the plate are principally taken into account as uncertainties in the reliability analysis of the bending behaviour of HFRP plates that was conducted in the current study utilising the Level I method in the LRFD concept. The inherent randomness in physical attributes is examined and simulated using Monte Carlo simulations according to the first order reliability approach (FORM). Following study of the random distribution, the chi-square test is used to identify the proper distribution type. The mean and standard deviation values can be obtained after the distribution type is known. Tensile strength (HFRP rebar) and moments of resistance (HFRP unidirectional plate) are simulated using Monte Carlo simulation (MCS).

II.RESULT AND DISCUSSION

The variability built into the analysis process is measured using experimental data from prior investigations. Based on the established resistance model and the load model(s) acquired from the literature, a structural reliability study is carried out. The calculation for the confidence index is. The ratio of the active load moment and the dead load moment is calculated using the shape employed for all FRP-RC slabs and beams. Monte-Carlo simulations are used to determine the manufacturing process based on the ambiguity and bias of the physical characteristics, MF and CoV, VMF. The ambiguity of the analytical model is reflected by statistical bias, P MF, and CoV, VP VMF, which come out to be 1.08 and 15.2%, respectively, in the experimental findings that are available on the HFRP bars. The ductility resistance of HFRP plates is the main topic of this study, which also considers additional failure modes as adhesion and shear.

The current investigation was carried out for slabs of reinforced concrete with longitudinal and transverse HFRP reinforcement. To create the appropriate failure mode hierarchy, potential failure modes are first outlined, and then primary failure modes (such as concrete bending and concrete fracture) are recognised and categorised according to their severity. For design purposes, the primary failure mechanism of breaking flexible concrete has been selected. When the reinforcement ratio is raised from 0.49 to 0.81%, the reliability index falls. A high confidence index for an HFRP gain ratio equal to or less than one is recommended in order to prevent the failure mechanism of the HFRP fracture. The reliability index is influenced by concrete's compressive strength. The M50 grade HFRP reinforced concrete was determined to have the highest confidence index.

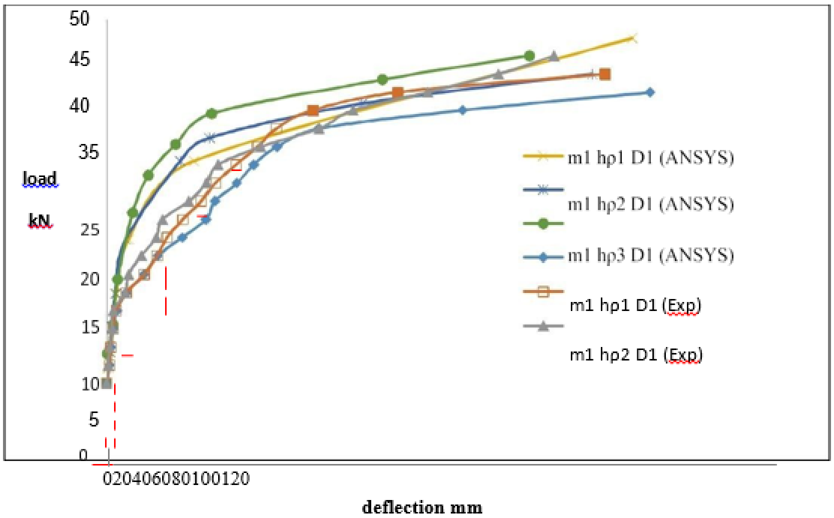

Figure 10 (ANSYS and experimental) comparison of the load vs. deflection of HFRP plates for various reinforcements ratios

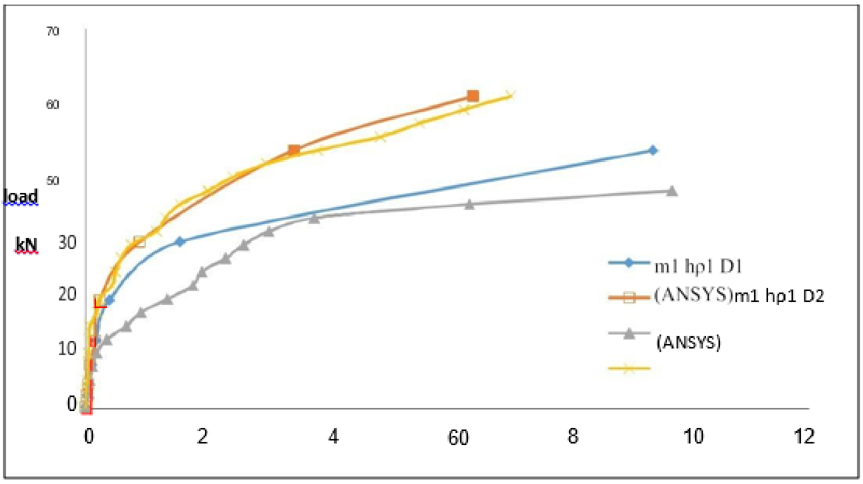

Figure 11 (ANSYS and experimental) comparison of the load vs. deflection of HFRP plates for various reinforcements ratios

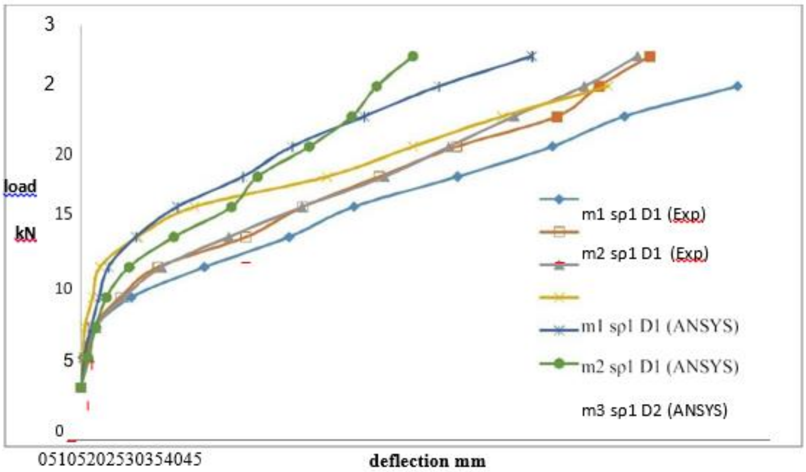

Figure 12 Analysis of load versus deflection for typical plates with various reinforcing ratios

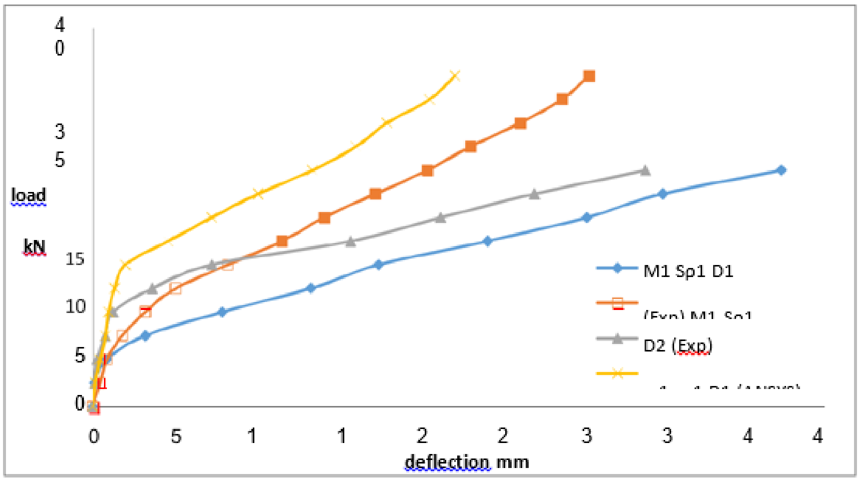

Figure 13 (ANSYS and Experimental) comparison of the load versus deflection of typical plates for various plate depths

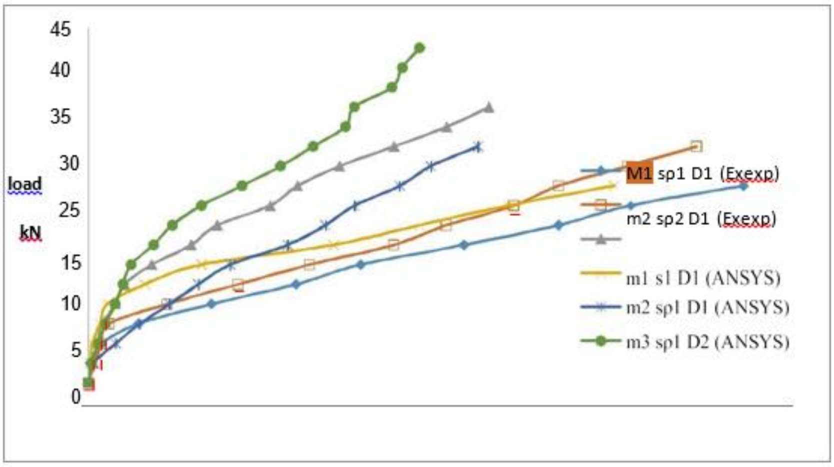

Figure 14 (ANSYS and Experimental) comparison of the load versus deflection of standard slabs made of various types of concrete

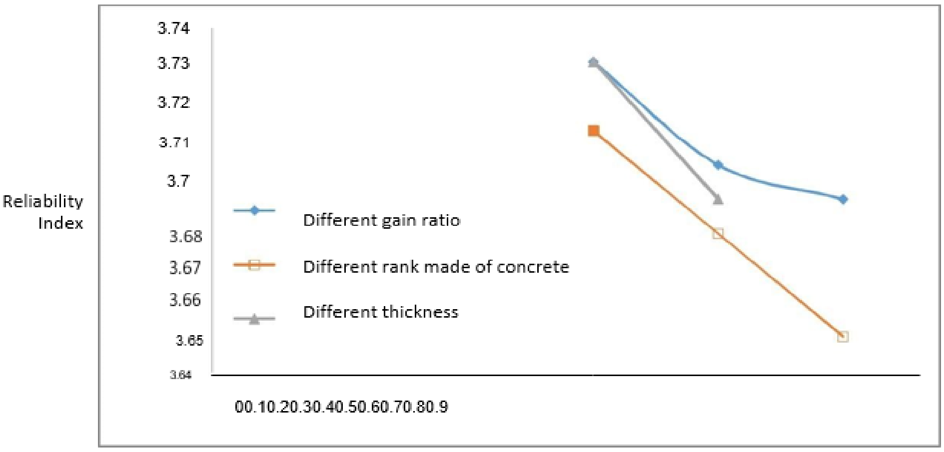

Figure 15 Comparison between the dependability index and the reinforcement ratio for HFRP plates that have been reinforced with various types of material

Comparison of a reinforced concrete unidirectional slab with HFRP grades M40 and M30. When the thickness of HFRP reinforced concrete unidirectional slabs is increased, it is seen that the dependability index somewhat decreases for slabs that are 120 mm thick compared to slabs that are 100 mm thick. A structural reliability analysis is then used to identify the appropriate resistance factors. Based on these experiments, the confidence indices for all HFRP plates fall between 3.36 and 3.73. The target credibility index for the current study is 3.66 for HFRP Reinforced Concrete with One Way Plate and for 3.36. The strengthened concrete slabs for HFRP are defined as having a reinforcement ratio of 0.75 for low reinforcement and 0.76 for high reinforcement in the current study. The power reductions factors suggested in earlier studies are fairly close to these values.

III.CONCLUSION

The created load deflection charts show the differences between the results from the FEM (ANSYS). The stiffness of the meshing is what causes the FEM's minimal deflection. The outcomes also clarify the role of adhesive slip and stress hardening. Comparative analysis reveals that the experimental deflection exceeds the FEM deflection by a factor of 1.03 to 1.37. Using the LRFD principle, the reliability index and resistance factors have been assessed. The implementation of Monte Carlo Simulation (MCS) is used to produce random parameters. Finally, in order to prevent the failure of the HFRP rupture, a high confidence index is proposed for the HFRP gain ratio equal to or less than one. Based on these investigations, the index of confidence for all ranges from 3.664 to 3.36.

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