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Analytical and Experimental Study on Strengthening of using Carbon Fibre

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ABSTRACT: this new paper describes using CFRP to anchor strengthening systems. Fiber-reinforced polymers (CFRP) Carbon fiber reinforced polymers (CFRP) are used to strengthen concrete. CFRP is a two-part heterogeneous exterior reinforcing material. The ability to swiftly apply CFRP materials with minimal disruption to a structure's use and without changing its shape or weight makes it an attractive approach for strengthening existing elements. These filaments create a single carbon fiber strand, which is woven with a transverse thread (glass or nylon) to make a fabric-like sheet. Experimental and numerical investigations predict the bearing capacity of reinforced concrete beams strengthened using CFRP composites.The effect of CFRP thickness and length on failure load and ductility is explored, and failure load, stiffness, ductility, and fibre stress curves are provided. Carbon fiber sheet thickness reduces stresses. Improved beam cracking.Crack propagation changes with fiber length, affecting beam failure mode. Fluctuation in sheet length causes interface stress variation de-bonding failure, if not properly considered in design, can reduce strengthening effectiveness.

KEYWORDS: CFRP, Carbon Fiber, Stiffness, ductility, Crack Propagation, Time & Motion study, rate Analysis

I. INTRODUCTION

Carbon fiber reinforced polymer (CFRP) materials are a new way to repair concrete damaged by overload, impact, corrosion, fire, or settling. CFRP laminates are woven fabrics impregnated with highstrength structural epoxy and thin carbon fiber strands. When built appropriately, CFRP has strong axial tensile strength in the carbon fiber strands' direction. When strengthening or rehabilitating a concrete structure, CFRP materials are lightweight, strong, and non-corrosive. CFRP is a practical and attractive approach for strengthening existing elements since it can be applied quickly with minimal disruption to a structure's use and without changing its shape or weight.

Most of this study has been done on small test specimens, which may not reflect actual steel reinforcement configurations. Much study has been done on using CFRP for structural applications. In many experimental experiments, shear forces can only be communicated between the two materials through the CFRP laminates' interface with the concrete. The epoxy-concrete interface has the least strength in the CFRP strengthening system. CFRP laminates separate from concrete at 40 to 50% of their ultimate capacity. Direct pull off tests measure the condition of the substrate concrete (original or refurbished) and surface preparation. Designers must address this unfavorable limitation on CFRP functional strength due by premature de-bonding failure.

It's practically impossible to avoid premature de-bonding failure if the CFRP laminates aren't correctly attached, and various researchers have stressed the need of end anchorage. Most of the CFRP anchorage methods being examined are mechanical and involve pinning laminate ends to concrete.



Figure 1.1: Schematic diagram of a CFRP sheet

Figure shows that CFRP is an anisotropic material, meaning its high strength is maintained in the fibers' direction. Mechanical parameters determine this categorization. It's also an elastic material that retains its stress-strain relationship linear up until failure, with final strain values of 1 to 1.5 percent. This means a CFRP system can give high strength with less material.

This new research describes using CFRP to anchor CFRP strengthening systems. CFRP anchors avoid de-bonding failures in CFRP laminates and produce complete tensile strains of the carbon fiber material. CRPE

Carbon Fiber Polymers (CFRP) The usage of carbon fiber reinforced polymers (CFRP) to strengthen concrete is growing. Two-part CFRP is an externally applied heterogeneous reinforcing



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material. First, a textile-like fabric of carbon strands; second, a high-strength structural epoxy or resin. A carbon fiber filament is 7 to 10 micrometers wide.



Figure 1.2: Layered CFRP sheet to obtain strength in two directions

No carbon fibers are woven transversely. Without these fibers, CFRP sheet can't resist perpendicular forces. For transverse strength, at least two layers of carbon fiber sheets must be applied to the concrete substrate in an orthogonal pattern, with the longitudinal axes perpendicular to each other.

CFRP as a retrofitting material is expensive. Carbon fiber fabric is pricey compared to epoxy or resin. Carbon fiber reinforced polymers are stronger and more durable than glass or aramid FRPs. After installation, CFRP requires little maintenance. Many reinforced concrete applications use CFRP despite its higher cost due to engineers' durability concerns.

FRP laminates have lower tensile characteristics than FRP fibers. FRP bars have 50 to 70% fiber capacity, Precured systems 40 to 60%, and wet lay-up laminate systems 25 to 40%. Precured laminates have superior mechanical qualities than wet-laid laminates due to fiber volume.

Over time, reinforced concrete structures degrade, collapse, and lose their ability to bear earthquake, wind, and creeping loads. Earthquakes, wind, seismic, and creeping all contribute to this deterioration. As the structure deteriorates, its load capacity will decrease.

These filaments comprise a single carbon fiber strand, which is woven with a transverse thread (glass or nylon) to generate a fabric-like sheet. The carbon fiber sheets are impregnated with epoxy or resin, and the fibers act as a unit. Figure shows a SEM picture of a FRP.

II. LITERATURE REVIEW

Review on strengthening of reinforced concrete columns by cfrp jacketing, Kushappa M K, G V Nandi, Azhar Jamkhandi, Sagar Gouli, Tasmiyakousar Shamannawar, AliyatasleemManiyar, International Research Journal of Modernization in Engineering, Technology and Science, Volume:04/Issue:04/April-2022

Seismic protection increases a structure's earthquake performance. Recent Indian earthquakes damaged lives and property. New materials and processes can repair, seismically fortify, and upgrade buildings. Repairing structures requires the right materials, techniques, and procedures. Innovative structural repair solutions beat traditional approaches. FRP is a composite material used in civil engineering to resist deformation and load. Carbon fiber reinforced polymers (CFRPs) are stiffer and lighter than standard materials. It's sometimes preferable to reinforcing steel. Laterally jacketing RC columns increases deformation and load resistance, FRP jacketing improves RC column performance by supporting axial load and creating lateral confining pressure. This paper examines the analytical and experimental behavior of RC columns under axial loading and their seismic behavior (lateral stability). Composite, CFRP Sheets, RCC Column

Numerical investigation and cost analysis of FRP concrete Unidirectional hybrid slabs, amirmahboob and amirrezaeskenati, Int. J. of Applied Mechanics and Engineering, 2021

Reinforcing concrete with FRP is common. FRPs are an efficient alternative to other techniques of reinforcing concrete in harsh environmental conditions that cause corrosion and deterioration. Fiber Reinforced Polymer (FRP) composites are commonly used in steel substitution during revival due to their lightweight, high strength, and high corrosion and fatigue resistance. This study includes 3-point bending testing. On several models, examine the effects of Carbon, Glass, and Aramid fibers to determine their costs. Also, an experimental model for testing FEM results showed broad agreement with the experimental statement regarding the load-displacement Curve. After validating the models, alternative designs such as FRP type, position, and amount were numerically examined for loadbearing capacity. The best design uses GFRP and has a load-bearing capacity of 9 kn. CFRP, GFRP, AFRP, hybrid slabs, simulation, prices.

Pre-Load Effect on CFRP-Confinement of Concrete Columns: Experimental and Theoretical Study Francesco Micelli, AlessioCascardi and Maria Antonietta Aiello, June2021

External confinement increases concrete columns' axial compression strength. FRPs have been extensively investigated in this context. In practice, FRP-confinement is put on loaded columns, which can already be considerably distorted. This article investigates if a pre-existing axial load affects concrete FRP-confinement. The research program also attempted to develop a new analysis-oriented model for predicting the compressive strength of FRP-jacketed concrete columns based on the axial load before confinement. Small concrete cylinders were loaded, contained with Carbon FRP, and then subjected to destructive axial compression testing. Simulated loads included the unloaded state. FRP; column; AOM; preload

Axial testing of concrete columns confined with Carbon FRP: effect of fiber orientation Renato Parretti, Co-Force America, Inc., Rolla, MO, Antonio Nanni, University of Missouri-Rolla, Rolla, 2021

FRP laminates comprised of carbon fibers with several fiber orientations, including 45-degree direction, were tested for concrete confinement (circular and rectangular). 45-degree FRP laminates are compared against unidirectional laminates of different manufacturers and amounts. 45-degree FRP laminate strengthened rectangular columns have a somewhat lower ultimate



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capacity than those with hoop fibers. 45-degree columns are more ductile because to the fiber orientation's enlarged failure zone. Larger failure zones allow for greater energy dissipation and stress redistribution. Numerical analysis confirms lab results. We suggest using FRP laminates with varied fiber orientations in concrete confinement design guidelines.

Strengthening of column & beam by carbon fiber reinforced polymer (CFRP) A. M. Kolekar, S. S. Shinde, Y. S. Nikam, T. R. Patil, R. V. Patil, S. S. Patil, S. R. Gavade, N.S. Pawar, P.S. Patil, 2021, IRJET, International Research Journal of Engineering and Technology

This research paper was developed by examining previously published research papers on topics such shear failure of beamcolumn joints as the main cause of collapse of numerous resistant moment frame buildings after recent earthquakes. In this study work, carbon fiber-reinforced polymer (CFRP) sheets that increase shear strength and ductility of seismically weak beam-column junctions are explored. First, CFRP sheets were epoxy-bonded to beam and column joints. Column & Beam, Strengthening, CRP

Comparative Study on Strength Properties of CFRP Wrapped Concrete Elements with Conventional Concrete, A.R. Pradeep, M.I. Basavalinganagowda, C. Rangaraj, Journal of Interdisciplinary Research. Vol. 1(2), July - Dec. 2020,

Many structures are in distress and partially damaged due to design flaws, construction deficiencies, and natural influences. These structures need to be modified to extend service life. CFRP is one of the best materials for retrofitting damaged structures, according to study. It can reinforce damaged structures. CFRP consists of glass, carbon, and steel wires embedded in a polymer matrix. The polymer matrix (epoxy resins) functions as a binder, shields the fibers, and transfers loads between them. This article compares conventional and CFRP-wrapped concrete's strength. M40 grade concrete mix proportion designed; material attributes tested. Compared to normal concrete, compressive strength increased by 15%, flexural strength by 10%, and split tensile strength by 30%. Retrofit, Flexural Strength, Polymer, Compressive Strength.

Comparative analysis of the reinforced concrete beam by using various forms of retrofitting techniques, lovneeshsharma, mohitbhandari, European Journal of Molecular & Clinical Medicine, 2020

This study aims to increase the endurance of beams by employing various jacketing techniques. In this research, I investigate two ways for retrofitting beams: reinforced concrete (RC) and carbon fiber reinforced polymer (CFRP) (CFRP). In this investigation, 100 mm of RC jacketing is employed on all four sides of the beam, along with varied thicknesses of CFRP sheets. After casting the beams, a point load test is performed on a loading frame machine to check for cracks, ultimate strength, and to compare the outcomes and costs of alternative reinforced concrete retrofit approaches. Comparing the deformation and stress behavior in ABAQUS and experimentally validates the analyses. This study found that RC jacketing strength rose by 63% and CFRP by 48.5%. The test results reveal that RC jacketing increases flexural strength. Beam, Carbon Fiber, Reinforced, Polymer jacket

Characterization of carbon fiber reinforced polymer strengthened concrete and gap detection with a piezoelectricbased sensory technique, ParitoshGiri , Sergey Kharkovsky, Xinqun Zhu , Simon Martin Clark, ShimaTaheri and BijanSamali, Structural Health Monitoring 2019,

In this research, a piezoelectric-based sensing technique is created to detect the gap between CFRP and early-age concrete. The suggested technique uses guided waves in a carbon fiber reinforced polymer plate stimulated and received by piezoelectric transducers positioned on the specimen's exterior. Fresh and early-age hardened concrete and two CFRP plates are measured. A sine burst signal activates a piezoelectric actuator, which produces a wave. Comparing gap signals reveals the gap. To measure the gap, we use correlation coefficient, peak-to-peak amplitude, and rootmean-square deviation. Comparing gap damage indices with earlyage concrete indices identifies and predicts shrinkage. Tiny transducers are used. One-sided, non-destructive and cost-effective concrete characterization; CFP, SHM, de-bond, gap, piezoelectric transducers, guided waves, NDT

Comparative study of beams by using different types of retrofitting techniques, MansiSaini, Aditya Tiwary, International Journal of Civil Engineering and Technology (IJCIET), March 2019,

This study aimed to increase beam strength using several jacketing processes and determine the best cost-effective solutions. This paper retrofitted beams with reinforced concrete (RC) and carbon fiber reinforced polymer jacketing. In this investigation, 100 mm RC jacketing is used on all four sides of the beam and varied thicknesses of CFRP sheets are used. The point load test is done on a loading frame machine to examine the fracture, ultimate strength, and cost of all retrofit techniques for reinforced concrete. ABAQUS software was also used to analyze and validate deformation and stress behavior. RC jacketing strength rose 63% and CFRP by 48.5%. The test results reveal that RC jacketing increases flexural strength.

Retrofitting of Reinforced Concrete Beams using CFRP Jacketing, M. Leeladhar Reddy, A.V.S SaiAkhil, G. Sri Harsha, International Journal of Recent Technology and Engineering (IJRTE), April 2019

After a structure's design life, it must be repaired or upgraded. Retrofitting strengthens and improves a defective structural member. The retrofit aims to reinforce the building to meet its design load. This document An E-Tabs RCC structure has been designed. Due to adding levels above the existing structure's top floor, the design loads rose. Some of the bottom-floor columns collapsed, therefore they were modified with CFRP jacketing in ANSYS to boost strength to satisfy design standards. Design loads, flexural stress, jacketing, longitudinal reinforcement, retrofitting.



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Repairing and Strengthening of Damaged RC Columns Using Thin Concrete Jacketing Bassam A. Tayeh, Mohammed Abu Naja, Samir Shihada, and Mohammed Arafa, June 2019

This study evaluates thin concrete jacketing's ability to repair fractured columns. (An experiment cast nine 300mm reinforced concrete column specimens with 100mm, 150mm, and 170mm cross-sections. 36 100mm100mm and 300mm column cores were made. 90% of the cores' ultimate axial stresses killed them. All four sides of the columns were jacketed with 25 and 35mm. Group 1 used conventional concrete with a maximum aggregate size of 4.75mm and steel reinforcement to jacket 18 column cores. Group employed ultrahigh-performance fibre-reinforced 2 selfcompacting concrete with steel reinforcement. Group 1 columns have twice the ultimate load capacity of unjacketed columns and the same axial capacity. Group 2 specimens have a higher ultimate load capacity than reference columns. Surface preparation was best with shear studs.

Strengthening of short R.C. columns by FRP jackets, mahmodsamak, ehablotfy, manarahmed, April 2018

R.C. columns use fiber-reinforced polymers. This is a concrete reinforcement alternative. Six FRP-reinforced specimens will be evaluated and compared to FEM results. Shape separated tested columns. The first contains three 200-mm-diameter circular columns and the second has three 200-mm-long square columns; control specimen, partially strengthened by GFRP strip and fully strengthened by GFRP sheet. Each column has 6@200mm stirrups and 412mm reinforcing. ABAQUS runs 18 simulations. Externally restricted FRP sheets improve short concrete column strength and ductility. A design equation is given for tiny GFRP-wrapped concrete columns. Strength, ductility, GFRP, ABAQUS, short RC columns

A Comparative Study of RC Beams Strengthened with GFRP Laminates, S. T. Rushada, S.K. Duggalb, K. K. Shuklac International Journal of Engineering Technology Science and Research IJETSR, August 2017

Four GFRP laminates can strengthen RC beams. Four-layer SCP, SAP, ASCP, and ASAP laminates. Experimentally examined and ANSYS-validated flexural behavior of basic RC beams. Castings included five sets of five M20 beams. Determination of strengthened beams' flexural capacity, ductility, and stiffness. Symmetric cross-ply laminate is best for strengthening RC beams. Flexure, GFRP, Laminate, ANSYS

Behaviour of square concrete column confined with carbon fiber rienforced polymer (cfrp) sheet, Anilkumar D D, Mutturaj A D, Thippeswamy j, Umesh F M, Prof. Devi Prakash Upadya, International Journal of Scientific Development and Research (IJSDR), May 2017 IJSDR

An experiment determines how to strengthen concrete columns with CFRP. Carbon fiber reinforced polymer sheet (CFRP) is externally bonded to concrete to improve flexure and shear strength, retrofitting, and confinement. Columns are wrapped with epoxy-impregnated carbon fiber sheet. Carbon fiber reinforced is also utilized for structural repair and strengthening. This procedure strengthens a column under varying loads. Nito wrap (CF) is a carbon fiber composite solution for strengthening columns, beams, retaining walls, and slabs of load-bearing constructions. Ideal for earthquake retrofitting carbon fiber, CFRP, structural repair, and strengthening external concrete columns

Experimental and analytical analysis of reinforced concrete columns strengthened with CFRP, Carlos Valbson dos Santos Arau´ jo, Ricardo Jose´ Carvalho Silva, Springer International Publishing Switzerland 2016

Improved building technology annually, new building materials, equipment, and procedures develop. The inventions strengthen reinforced and pre-stressed concrete. These aren't just new buildings. Repair and strengthening processes were established. This study evaluated carbon-fiber-reinforced polymer mantles on concrete columns. The experiments examined mantles' potential to increase axial compression resistance and column structural behavior. Four experimental columns and one control column were axially crushed. Abaqus simulated column tensions. According to evidence, strengthening columns increased their resilience. The column with the highest strengthening rate bore 42.8% more than the reference column. These results led to a basic column resistance model. CFP, axial compression, CRC

Strengthening of Beams Using Carbon Fibre Reinforced Polymer, RatanKharatmol , PankajSananse, Rohit Tambe, Ms.RakshaJ.Khare, International Journal of Emerging Engineering Research and Technology, June 2014

Accelerating infrastructure growth; several reinforced concrete and masonry buildings are built annually. Many decay or become unsafe because to use, loading, design configuration, poorer building materials, or natural calamities. Safety repairs and retrofits are big business. A civil structure may need strengthening or restoration due to weakness, stiffness, ductility, and durability. Epoxy-bonded CFRP can strengthen beams, columns, and plates. CFRP has surpassed traditional structural repair and strengthening methods. The study compares RCC and CFRP-bonded beams' load-carrying and ductility. An experiment examines the structural behavior of R.C.C. beams wrapped with carbon fiber of various thickness, orientation, and length to enhance flexural and shear capacity. Epoxy, flexural, retrofitting, repair

Retrofitting – comparative study of RC jacketing and FRP wrapping, PrathameshDingorkar and AyushSrivastava, International Journal of Civil Engineering and Technology (IJCIET), September-October 2016

Time deteriorates structures beyond repair. Some structures can't be closed for lengthy reconstruction. Retrofitting is an effective way to fight defiance. This article compares RC jacketing vs FRP wrapping for increasing strength. RC jacketing and FRP wrapping strength increases are compared. This study evaluates two retrofitting approaches for deteriorated structural members. The analysis will enable the structural engineer select which retrofitting option to use to boost strength. Confinement, Ductility, FRP, RC, Retrofitting, Seismic Performance



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Performance Analysis of CFRP Composite Strips Confined RC Columns under Axial Compression, J. Raja Murugadoss, Byung Jae Lee, JinWook Bang, G. Ganesh Prabhu, and Yun Yong Kim, April 2015

In order to reduce the cost of FRP composite strengthening, an experiment was conducted using CFRP composite strips. 20mm and 40mm wide CFRP composite strips were utilized to restrict columns. The test results of the column restricted with narrower spacing (20 mm) demonstrated strong control of axial deformation and increased strength capacity to 99.20%. The column surrounded by wider strips (40 mm) failed from concrete crushing before the CFRP strips reached their ultimate strain. The CFRP strips' embodied energy couldn't be successfully used. This study evaluated the stress and strength enhancement ratio of full-wrapped columns with earlier studies. From the results, it's recommended to employ 20mm-spaced CFRP strips to improve the RC column's strength. This wrapping technique is also more cost-effective than full wrapping.

Strengthening of RC Column using GFRP and CFRP, K. P. Jaya, JessyMathai, Hindustan Institute of Technology & Science, Chennai, India, 2012

Political and social issues surround earthquake-prone building retrofitting. Most Indian buildings are earthquake-prone, even in high-risk areas. Since 1980, India has had severe earthquakes. Such events have shown the built environment's vulnerability. The building needs seismic retrofitting. This study compares GFRP and CFRP-reinforced concrete beam-columns under reverse cyclic loading. IS 456-2000 reinforced concrete columns have less earthquake flexibility. Beam-columns need seismic containment. FRP composites are popular. RC beam-columns with and without FRP were tested. One sample lacked GFRP or CFRP, three had 2, 4, and 6 layers, and two had CFRP. The samples were loaded axially and laterally. GFRP and CFRP jackets improve RC beamcolumn ductility and energy absorption.

III. RESEARCH METHODOLOGY

Aim of Project

"To Analysis the crack propagation changes with fiber length, affecting column failure mode; Fluctuation in sheet length causes interface stress variation. De-bonding failure, if not properly considered in design, can reduce strengthening effectiveness."

Problem Statement

"To examine experimental and analytical column structural models to determine column strengthening stresses. Carbon fiber rate analysis and time-and-motion studies t o analyze CFRP's strength improvement"

Objectives

- To study experimental and analytical structural models of column
- To find out stresses of strengthened of Column

- Constitutive models of CFRP composite and steel
- To find rate analysis and time and motion study in carbon fibre
- To analyze the increase of strength using CFRP

Panacea of CARBON FIBRE STRENGTHENING Common reasons for FRP structural strengthening;

Durability problem due to poor or inappropriate construction materials

Inadequate design or construction

Aggressive environments not properly understood during the design stages

Increased loading requirements due to change of policy use of structure

Increased life - span requirements made on ageing infrastructure Exceptional or accident loading

Carbon fibre cloth wrapped foundation column is the most mature technology for strengthening concrete structures and building high-rise buildings

After the concrete is poured, if the column/ beam/slab/ footing fail, then implement a carbon fibre wrapping system to repair and achieve the expected strength

In place experiencing seismic activity or earthquakes, carbon fibre wrap column are the key to seismic reinforcement of concrete structures

Turning residential properties into commercial properties, the changed load pattern now fall on the structure, making it necessary to strengthen the structure to maintain the new and increased capacity. Here carbon fibre wrapping column is also an effective technology reinforcement system.

Carbon fiber is most commonly used to reinforce industrial structures, subject to heavy loads and mechanical vibrations. In areas with extreme climate conditions or high humidity, the structure is strengthened and carbon fiber reinforced columns can be well developed.

Similarly, in the case of structural repair, or when deflection occurs in the structure, when the column begins to sag, or when repairing a defective structure, carbon fiber reinforced columns are the most popular adjustment and reinforcement system

Advantages of fiber Reinforced polymers (FRP) composite strengthening

- Economical and durable
- Easy application
- Extremely high tensile strength
- Outstanding fatigue behavior
- Absolute corrosion resistance
- Ability to upgrade structure while in use
- Upgrades possible even with limited access



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Methodology For Repair and Strengthening of columns By Using Carbon Fibre Wrapping (CFRP)

Surface preparation:

The surface of the beams at bottom, and also the sides shall be grinded by using a hand grinding machine to remove all protrusions imperfections, traces of any curing membrane etc and then cleaned with a spray of water jet or compressed air or wet cloth to remove all dust and lose particles.



Grinding of column for surface preparation

Surface preparation:

The surface of the beams at bottom, and also the sides shall be grinded by using a hand grinding machine to remove all protrusions imperfections, traces of any curing membrane etc and then cleaned with a spray of water jet or compressed air or wet cloth to remove all dust and lose particles.



Grinding of column for surface preparation

Provision of primer:

The cleaned and prepared surfaces shall be provided with a coat of Maxtreat Primer manufactured by Thermax Ltd using a brush / roller.

The primer shall be applied to a thickness of 100 - 150 WFT (Microns).



Application of primer on column for column strengthening

Provision of Epoxy Putty:

The surface imperfections if any, blow holes, pits etc shall be filled with epoxy Putty Maxtreat EPG of Thermax ltd to have a maximum area of surface contact with the fiber.



Application of putty on column for column strengthen Providing carbon fibre:

The surface applied with saturant shall provide with 400 GSM carbon fibre maxtreat fibrenet C of Thermax Ltd as per the details provide in the drawing the overlaps development length, extensions shall be as per the detailing show in the drawings.



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First wrap of Carbon fiber on column for strengthening

Carbon fiber reinforced plastic (CFRP) has been applied in aeronautics, aerospace, automotive and medical industries due to its superior mechanical properties. However, due to its difficult-tocut characteristic, various damages in twist drilling and chip removal clog in core drilling could happen, inevitably reducing hole quality and hole-manufacturing efficiency. This paper proposes the wave-motion milling (WMM) method for CFRP holemanufacturing to improve hole quality. This paper presents a motion path model based on the kinematics of the WMM method. The wave-motion cutting mode in WMM was analyzed first. Then, comparison experiments on WMM and conventional helical milling (CHM) of CFRP were carried out under dry conditions. The results showed that the hole surface quality of the CFRP significantly improved with a decrease of 18.1%-36% of Ra value in WMM compared to CHM. WMM exerted a significantly weaker thrust force than that of CHM with a reduction of 12.0%-24.9% and 3%-7.7% for different axial feed per tooth and tangential feed per tooth, respectively. Meanwhile, the hole exit damages significantly decreased in WMM. The average tear length at the hole exit in WMM was reduced by 3.5%-29.5% and 35.5%-44.7% at different axial feed per tooth and tangential feed per tooth, respectively. Moreover, WMM significantly alleviated tool wear. The experimental results suggest that WMM is an effective and promising strategy for CFRP hole-manufacturing.



Figure: Schematic illustration of (a) convention ultrasonic vibration cutting mode and (b) wave-motion cutting mode

Applied process for CFRP hole-manufacturing; however, various damages can happen during twist drilling of CFRP, such as delamination and tearing, resin depletion, surface cavities, fuzzing, hole-roundness errors, thermal damage. Damages usually occur due to the heterogeneous and anisotropic nature of CFRPs. These undesirable drilling-induced damages inevitably reduce the fatigue

strength of the hole, weakening the long-term performance of machined CFRP parts. Therefore, machining high quality and precise CFRP holes remains a challenge



Figure: Experimental



Therefore, the axial feed per tooth (fza) and tangential feed per tooth (fzt) can be changed by the axial feed per helical revolution (ap) and the revolution speed (ft). In order to evaluate the feasibility of WMM of CFRP whole, three groups of experiments were conducted, including surface integrity, hole exit damage, and tool wear experiments. All experimental parameters are listed in tables 1–3, respectively. Each experiment was conducted three times

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