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Ductility Factor Evaluation of Concrete Moment Frame Retrofitted by FRP Subjected to Seismic Loads

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Abstract – *Most of the reinforced concrete buildings that have been constructed are not earthquake resistant or have not sufficient and acceptable resistance. Therefore, these buildings need retrofitting with reliable, simple, and cost-effective retrofitting methods, particularly against lateral loads. Since a significant number of vulnerable buildings have already been designed, raising their seismic resistance in different ways can lead more or less to functional challenges and structural design changes. Building industry researchers have always tried different approaches to fix defects in concrete structures. Today the use of advanced composite polymer materials to reinforce and strengthen structures is developing. One of the most important goals of seismic standards for structures is to provide enough ductility, because under such conditions the structure will be able to dissipate a sufficient amount of earthquake energy. This article describes the role of polymeric fibers enhanced by the fiber-reinforced polymer (FRP) in reinforcing reinforced concrete structures. Therefore, the most fundamental steps to achieving this goal is an evaluation of the response modification factor (R) and the ductility coefficient (μ). Due to this important need, this study will present a formula that calculates the amount of plasticity in concrete structures. Three concrete moment frames of 3, 6 and 12 floors with and without composite FRP have been tested for finding this coefficient. In SAP2000, nonlinear static analysis (Push-Over) of the frames has been performed, and then factors of ductility and response have been determined from the base shear and the roof displacement curve.* ***Copyright © 2020 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Concrete Moment Frame, FRP, Push-Over Analysis, Response Modification Factor (R), Ductility Coefficient, SAP2000*

Nomenclature

OMRFs	Ordinary Moment-Resistant Full-scaled
FRP	Fiber-Reinforced Polymer
R	Response modification coefficient
$R\mu$	Ductility reduction coefficient
T	Period time of structure
μ	Ductility factors
μ_e	Materials ductility
μ_θ	Member's ductility
μ_δ	Factor indictor of general behavior of structure
V_y	Base shear matching to the highest inelastic displacement
V_d	Designed base shear
Δy	Maximum displacement at V_y
Δmax	Maximum roof displacement
Ω	Over-strength factor

I. Introduction

There are many building reinforcement methods due to the need to incorporate robust materials and price-effective retrofit methods, and due to structural defects (degradation of materials or aging, lack of maintenance, and earth quakes) damage to structural elements such as beams, columns, etc. There are several ways of strengthening for RC columns, focusing mainly on using various materials to surround the RC columns to increase the efficiency and the ductility of the bearings. RC, form steel, Fibre-Reinforced Polymer/Plastic (FRP) etc. are the widely used materials for wrapping [1], [2]. Reinforcing for wrapping with RC is a traditional way, also known as strengthening structure component with growing section area [3]. Generally, Earthquake-resistant economic structures attain suitable mechanical and structural properties, so there is an acceptable response under effective of earthquake. The deformation of a structure relies on its system and performance. Most buildings has been designed economically, especially the ones that include bending frame members with rigid connections and other indeterminate structure, by allowing their critical member to approach to the yield stress when earthquake been hit. Therefore, this means that the design structure resists lateral load level less than the amount needed to ensure linear elastic behavior. The outcomes of the analysis and experience show that an indeterminate

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structure can be designed again high earthquakes, by allowing inelastic deformation happened according to their performance base level and that means yielding member should have the ability to endure inelastic deformation without reducing their bearing capacity, in other words the mentioned member should have enough ductility in order to get the required seismic response [4].

The technique of reinforcing structure member with FRP is commonly used and is currently one of the highlights in the area of reinforcement [5], [6]. It may be classified into carbon fiber (CFRP), glass fiber (GFRP) [7]-[10], aramid fiber (AFRP) [11], basalt fiber (BFRP) [12], hybrid fiber (HFRP) [13] and other reinforcement methods, depending on various kinds of fibers. Among them, the most commonly discussed strategies of improving are CFRP and GFRP. To RC columns with axial compression, slight eccentric compression, or inadequate ductility [14], the FRP reinforcing approach is suitable. In most cases, once the bearing ability of broad eccentric columns is inadequate, layers of fiber mesh need to be wrapped in order to achieve a more distinctive reinforcing impact that is evidently uneconomic [15].

The benefits of the FRP reinforcement system are lightweight, high strength, resistance to corrosion, resistance to moisture, flexible design, usually without any need for overlap and adaptation to the paste criteria of arched concrete [16], whereas the drawbacks are the restriction of ambient temperature and a need to create special safety therapy. If the security is insufficient, fire and dude-made harm are simple to suffer [17]. FRP has the benefit of being quick and efficient in reinforcing broken circular RC columns, in particular, work on compressive quality of broken circular RC columns reinforced by FRP is still quite restricted in different countries [18]. While extensive studies have been performed on the RC elements and beam-column joints retrofitted by the FRP, only a small number has investigated the effect of the FRP composites on the general behavior of RC structures. Study of the FRP retrofitted RC frames output is very poor but many empirical studies have been conducted. The behavior of a complete-scale, four-story frame with shear walls has been examined by Balsamo et al. [19]. National and global stability has been strengthened and the joint displacement and the kinetic capacities have been improved with no loss of strength. Harries et al. [20] have studied the Possibility to use small amounts of FRP in order to ensure cross-sectional stability by combining FRP strips to cross-section flange components, thereby this increases the member's critical load, restricts plastic flow in cross-sectional flange elements, and promotes the manifestation of the member under cyclic loading of a well-formed and stable hysteresis response. Zou et al. [21] have examined a three-story structure that has been reinforced around its columns with FRP. The strength of the columns has been found out to improve whereas the stiffness increases slightly. Growing column stiffness can lead to greater seismic forces acting on the frame. The frame's failure mode has been modified from a side-sway system in columns to an adequate level of story degeneration with poor beamstrong column behaviour.

Pampanin et al. [22] have also studied the behavior of a three-story modified CFRP frame during quasi-static checks. The findings have showed that using FRP outside joints would lead to plastic hinges formed in the outside beams (instead of in the beam-column joints). Because of its ease, investigators have used a Nonlinear Static Procedure (NSP) or pushover analysis in order to analyze the earthquake output of RC frames [23], [24]. Nonlinear static (pushover) analysis is more suitable for weak and low-period frames than inelastic dynamic analysis [25], [26]. Makarios [27] has introduced a new nonlinear static (pushover) seismic technique to achieve the seismic requirements and the appropriate behavioral factors for multi-story RC spatial asymmetric structures.

Niroomandi et al. [28] have evaluated the efficiency of a retrofitted RC frame for the FRP. ANSYS software [29] has been used to obtain the moment-rotation relationship of the RC joints retrofitted with web-bonded CFRP, produced by Mahini and Ronagh [30]. In this paper, it is shown that, compared with the original frame, the output level and the seismic activity factor of the retrofitted FRP RC frame have been enhanced or even increased significantly. Since full post-peak activity is hard to achieve with ANSYS, Niroomandi et al. [28] have focused in their analysis on the peak strength of both the plain / reconditioned joints. Hadigheh et al. [31] have achieved increased moment-rotation rigidity of the FRP-retrofitted joints utilizing ABAQUS finite element software [32] and have demonstrated the superior quality of poor beam-strong column RC frames reinforced by FRP at joints. Hadigheh et al. [31] have conducted experimental and computational tests on an eight-story scaled-down and two ordinary moment-resistant full-scaled low-rise frames (OMRFs) refitted with FRP at the joints. In order to anticipate the seismic quality and the behavior factor of the retrofitted frames, additional rotational stiffness of the joints is introduced into pushover models. Findings suggest that retrofit of FRP is more efficient for low- and medium-rise OMRFs than for steel braces. More recently, Ronagh and Eslami [33] have suggested positive flexural reinforcement of an 8-story code-compliant research study of RC frames as a model of medium-rise structures utilizing Glass/Carbon Fiber-Reinforced Polymers (GFRP/CFRP). Ahmed Mahmoud Khalifa [34] has announced new containment strategy to enhance the impact of rectangular columns subjected to Carbon Fiber Reinforced Polymers (CFRP) wraps on containment. The findings show that the axial column potential is improved by the division of the rectangular cross section into squares. Increasing the CFRP strip width by using the same quantity of CFRP also has greater efficacy in expanding the total load capacity, rather than reducing the width by growing the thickness. Using the findings, an analytical model performed on rectangular columns subjected to CFRP has been checked that offers good cooperation with the findings. Benjabrou et al. [35] have used a non-iterative spectral approach to assess the seismic vulnerability of a clinic in Agadir, Morocco region, reputed for its high seismicity. Firstly, a Pushover approach has been used in the SAP 2000 by modeling the structure. Instead, the capability curve of the building's substructure, so obtained, will also be translated into ADRS format (Displacement, Acceleration, Response Spectral), instead superimposed with inelastic response spectrum of the site being considered, which will be transformed to AD Format (Acceleration Displacement) in accordance with the RPS 2011 (revised) in order to evaluate the output level. Finally, in order to deduce the weakness, they continue with the analysis of fragility curves as per RISK UE. By simulating and evaluating the actions of a model school building under tidal powers, Bendada et al. [36] have research the effect of tsunami on specific buildings.

Some of the benefits of this study are highlighted, such as the objectivity of the tsunami risk evaluation and the ability to analyze specific buildings that may, somewhat, represent a significant solution for tsunami emergency plans. Yasmin and Ja'afer [37] have explored the influence of the angle of orientation of carbon fiber sheets in reinforced concrete beams. The results have showed that the angle of orientation of carbon fiber has a considerable influence on the flexural response of reinforced concrete beams. For 45 inclined carbon fiber plates, the best performance is achieved. In addition, a parametric analysis is performed in order to examine the effect of angle of orientation of carbon fiber plates, plate depth and plate thickness on the action of reinforced concrete beams. Chunli Zhou et al. [38] have implemented the technique of constructing circular reinforced concrete columns covered with externally covered plates. The findings have showed that the bearing capacity of the ordinary segment of the RC column after reinforcement was about 80 per cent greater than before reinforcement, and to some extent, the results of FEM software have been consistent with theoretical formula calculation outcomes. During horizontal low-cyclic reverse loading plumper hysteresis curves, higher ductility factors, and equal viscous damping factor have been clearly improved in the columns after reinforcement, suggesting the energy dissipation efficiency, plastic deformation ability, and seismic output of the RC columns after reinforcing. Gopika and Suji [39] have been considered to be ground+10 storage RC moment resistant to 35 m×22 m layout house. The failed column is taken for retrofitting in ANSYS 18.1 Workbench software. ANSYS program adopts linear static analysis. Column deformation is exposed without jacketing. Then, concrete, metal CFRP and GFRP jacketing are done to limit column deformity. Upon looking at the results of the columns with the jacketing, concrete jacketing is found to be effective in minimizing deformity of failed columns. In this study, Beam-column joint has been modeled in ABAQUS software and extracted moment-rotation (additional stiffness) curve for beams and columns, SAP-2000 non-linear link element (NL-Link) has been used for the modeling of retrofitted FRP frames. These elements could simulate the equivalent additional stiffness of web-bound FRP beams.

This study's main objective is to show that FRP-retrofitting can improve the overall lateral efficiency of the RC OMRFs. This work introduces a simulated numerical ABAQUS model of reinforced concrete joints through FRP sheets, pre, and post network bonding. The model takes into account concrete strain softening, is tested toward findings, and its aimed to investigate the assessment of the ductility, response factor, roof displacement and base shear for concrete moment frames (3, 6, and 12 story) subjected to the seismic loads and contrasted with the guidelines of the existing seismic requirements and previous research.

In this work, Section II indicates in surface preparation for FRP to concrete bonding in order to achieve an effective strengthening of FRP and concrete contact. Bonding is based on the properties of concrete, composite, and adhesive, and is very important in bonding concrete beams with FRP to prevent sudden failure. Section III shows calculations based on nonlinear static analysis (Pushover) of ductility and response adjustment factor used. Section IV demonstrates three-building (two dimension 3-2D) theoretical analysis with 3, 6, and 12 stories. All the frames have 5 m wide, 3.5 m floor height, and three bays. The frames have been analyzed 6 times, three nonlinear pushover analyzes without FRP (NSP-N), and three nonlinear FRP (NSP-F) pushover analyzes have been also conducted. Section V shows the findings and explanation of ductility, response modifying factors, roof displacement, and base shear values with and without FRP for 3, 6, and 12 frame. The results appear to be a significant improvement in structural behaviors under seismic loads for 12-story building with FRP better than other non-FRP buildings.

II. Surface Preparation for FRP to Concrete Bonding

Bonding relies on the properties of concrete, composite and adhesive and is very important to prevent sudden failure when bonding concrete beams with FRP.

FRP components consist of high tensile strength fibers fixed in an epoxy matrix and offer excellent corrosion resistance, light weight, high strength to weight ratio, high mechanical strength, quick and cost-effective repair or repair of beams, slabs or columns [40], [49].

Surface preparation is ideal for achieving an effective reinforcement of FRP and concrete contact. Furthermore, stress transferred among concrete structures and externally bonded FRP plates depends on the quality and efficiency of bonding among FRP components and concrete. [41]. The material properties of the epoxy matrix of the fibers along with the properties of concrete substrates like roughness, strength, cleanliness of the concrete surface are the essential obligation of consistency or durability of the bond [42]. Epoxy resins are often used to bind them together based on their superior adhesive capacity for both FRP and concrete.

Many times when epoxy adhesives are used, water, alkalis and other pollutants from the surroundings can react with the epoxy affecting the healing level and the degree of healing. These aggressive effects on the epoxy considerably diminish the durability and mechanical properties of the FRP-concrete bond [43]. Unwholesome degradation in fatigue can occur when RC beams are exposed to load repeats. [44] has centered on fatigue strength and also on projections in the fatigue cycle of RC beams. It highlights the desire to improve the efficiency of fatigue and increase the fatigue life of RC beams using a fiber-reinforced polymer reinforcing device.

III. Calculation of Ductility and Response Modification Factor Based on Nonlinear Static Analysis (Pushover)

Ductility can be defined as an ability to support tensile loads even after primary cracking or is the capacity of a material or a structure to dissipate energy by plastic deformation during impact or seismic loading [45]. In addition, ductility can be considered as a definition of material, member and all structure, these three types of ductility in term of numerical values has a big different and each other show an important role in seismic design.

Materials ductility μ_e means bearing capacity of plastic defamation, whatever value of μ_e has been big that means that the behavior of the structure against earthquake will be sufficient and minimum amount of μ_e means brittle materials and low seismic behavior.

Member's ductility μ_θ explains the ability to afford inelastic deformation with damaging in connections or structural member, so the minimum value of this factor means infelicitous ductility behavior.

μ_δ Factor indictes the general behavior of structure, in other word the building capacity to undergo deformation after primary design [46].

The three ductility coefficients should obtain the formula (1):

$$\mu_e > \mu_\theta > \mu_\delta \tag{1}$$

Composites (FRP), as the name implies, are physically combination of two or more materials that have a particular property; these properties count on the properties of the components and the method of their composition.

In this technique, the forces or lateral displacements extended to the structural model are gradually increased and at every step, decrease of stiffness caused by the elements or loss of resistance in the plastic joints has been considered, increasing load continued until all the members exceed to their yield point [48].

The typical response envelope relating force to deformation [48] and can be established from either testing or a pushover analysis. Initially, the structure responds elastically, followed by an inelastic response as the lateral forces increase. A variety of plastic hinges shape throughout the structure, resulting in a resistance-level system V_y. Generally, in Pushover analysis, convert base shear–displacement curve for two-line. Thus, by equating the capacity curve as a two-line diagram, all the characteristics of the behavior of the structure are extracted [25]. According to Federal Emergency Management Agency [47], the ductility and response modification factors are obtained from the following relations:

$$\mu = \frac{\Delta \max}{\Delta y} \tag{2}$$

$$\begin{cases} R\mu = 1 \quad \text{for} \quad T < 0.03 \text{ s} \\ R\mu = \sqrt{2\mu - 1} \quad \text{for} \quad 0.5 < T < 0.12 \text{ s} \\ R\mu = \mu \quad \text{for} \quad T > 1 \text{ s} \end{cases} \tag{3}$$

$$\Omega = V_y / V_d \tag{4}$$

$$R = R\mu \times \Omega \tag{4}$$

IV. Analytical Study

The prototype structure that been selected in this paper is three building (two dimension 3-2D) with 3, 6 and 12 story. All the frames have three bays with 5 m width, 3.5 m floor height. In addition, the frames analyzed 6 times, three nonlinear pushover analyses without FRP (NSP-N) and three nonlinear pushover analyses with FRP (NSP-F) have been executed. All the beam are subjected to live load of (1 ton/m) and dead load (1.5 ton/m). Other properties are:

- Concrete moment resistant frame (R=5);
- Important factor (I=1);
- Soil type (C);
- Seismic zone factor (A=0.3);
- Compressive strength (F'_c)=25 MPa and yield strength (F_y)=420 MPa.

For shear and flexural retrofitting, FRP is used in form of sheets for wrapping onto the beam concrete surface and for increasing their ductility (Fig. 2).

In this analysis, the RPC properties shown in Table I (elasticity module, unit Weight, yield stress and thickness) have been used. FRP has been used to enhance structural behavior.

Tables II-IV illustrate the results of designing for beams and columns for buildings of 3, 6 and 12 floors respectively by using ETABS software and according to ACI 318-14 code.

TABLE I
FRP PROPERTIES

Type	FRP Properties			
	Modulus of elasticity (E) [T/m^2]	Unit Weight [T/m^3]	Yield stress (F_y) [T/m^2]	Thickness [mm]
CFRP	2.3×107	1.85	3.79×105	1.2

TABLE II
PROPERTIES OF THREE STORY SECTIONS

Floor No.	Column	Beam
1st floor	50×50×10ϕ16 mm	50×30×3ϕ25 mm
2nd floor	50×50×10ϕ16 mm	50×30×3ϕ25 mm
3rd floor	50×50×10ϕ16 mm	50×30×3ϕ25 mm

TABLE III
PROPERTIES OF SIX STORY SECTIONS

Floor No.	Column	Beam
1st+2nd+3rd floors	50×50×10ϕ 25 mm	50×30×3ϕ25 mm
4th+5th+6th floors	50×50×10ϕ16 mm	50×30×3ϕ25 mm

TABLE IV
PROPERTIES OF TWELVE STORY SECTIONS

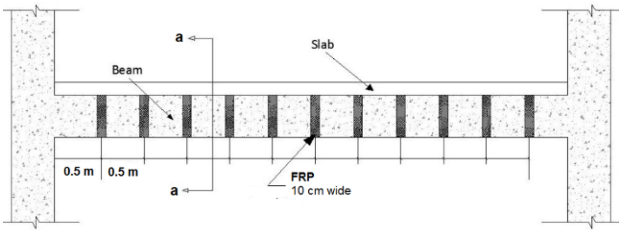
Floor No.	Column	Beam
1st+2nd+3rd floors	50×50×12ϕ 32 mm	50×30×3ϕ25 mm
4th+5th+6th floors	50×50×12ϕ25 mm	50×30×3ϕ25 mm
7th+8th+9th floors	50×50×10ϕ25 mm	50×30×3ϕ25 mm
10th+11th+12th floors	50×50×10ϕ16 mm	50×30×3ϕ25 mm

Subsequently, Beam-column joint has been modeled in ABAQUS software and extracted moment-rotation (additional stiffness) curve for beams and columns, Thus SAP-2000 non-linear link factor (NL-Link) has been used to model the retrofitted FRP frames using nonlinear static analysis (Push-Over). Such elements will approximate the equivalent extra rigidity given by web-bounded FRP sheets to the beams.

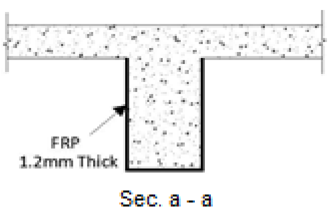
Figs. 1 show the section of beam bounded by FRP sheets from three sides, FRP sheets thickness are 1.2 mm, in order to improve structural behaviors under seismic loads.

V. Results and Discussion

Ductility, response modifying factors, roof displacement, and base shear have been achieved using nonlinear static analysis (Push-Over). Figures 2-4 provide the relation between roof displacement and base shear curve with and without FRP for 3, 6, and 12 story structure respectively.



(a) Details of rectangular strengthened beam with diagonal anchorage



(b) Beam section bounded by FRP sheet

Figs. 1. Modeling of rectangular reinforced concrete beams

Table V and Figures 2-4 clarify the results of base shear and roof displacement values for 3, 6 and 12 frames with and without FRP respectively. Based on FRP use for structural members of 3, 6, and 12 story, base shear and displacement enhanced by about 3.8%, 23.2%, and 37.3% for base-shear and about 11.1%, 11.3%, and 13.6% for displacement respectively. In this research, the results show a significant enhancement in structural behaviors under seismic loads for 12 story building with FRP better than other buildings without FRP.

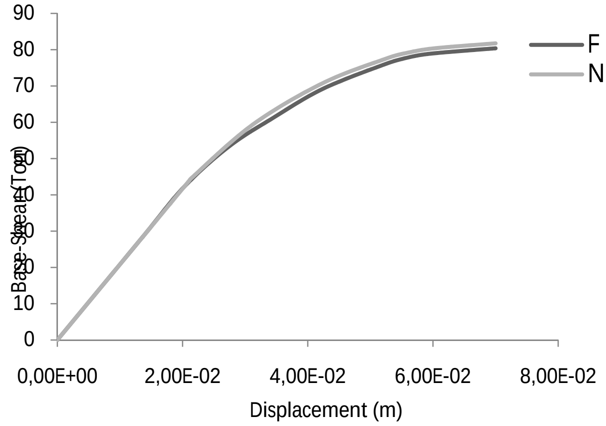


Fig. 2. Base shear – displacement curve for 3 story frame with and without FRP

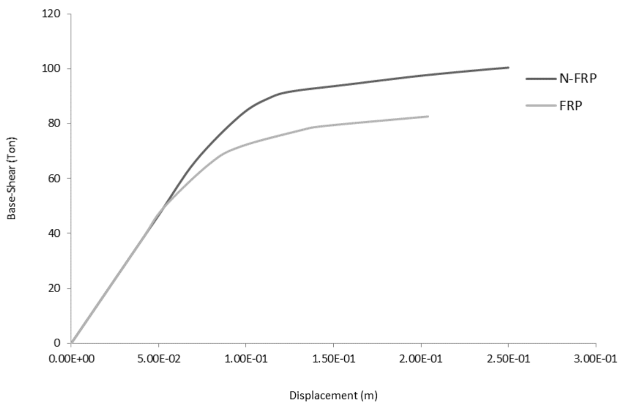


Fig. 3. Base shear – displacement curve for 6 story frame with and without FRP

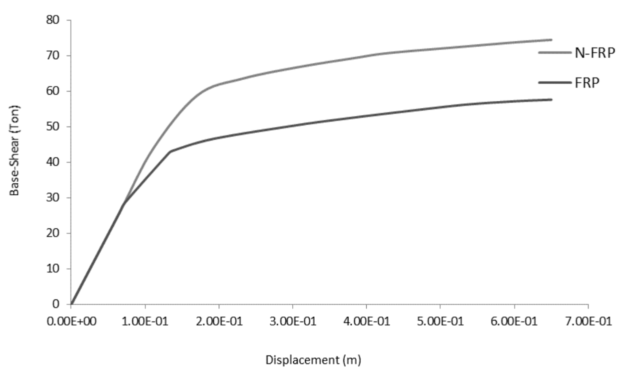


Fig. 4. Base shear – displacement curve for 12 story frame with and without FRP. FRP represents the fiber reinforced polymer, N-FRP without fiber reinforced polymer

TABLE V
DUCTILITY AND R-VALUES FOR 3, 6, AND 12 STORY FRAMES WITH AND WITHOUT FRP

Frame Type	D_y (mm)	D_u (mm)	V_d (Ton)	V_y (Ton)	μ	$R\mu$	Ω	R
3-St.	31.4	74.0	44.59	65.44	2.36	2.36	1.47	3.46
3-St.-FRP	30	66.6	42.42	63.06	2.47	2.47	1.49	3.67
6-St.	93	226.0	66.36	87.00	2.43	2.43	1.31	3.19
6-St.-FRP	75	203.0	49.60	70.60	3.00	3.00	1.42	4.28
12-St.	157	671.0	43.80	62.30	4.27	4.27	1.43	6.10
12-St.-FRP	114	590.48	28.43	45.36	5.93	5.93	1.60	9.46

Table V and Figures 5 and 6 illustrate the results of response modification factor and ductility values for 3, 6 and 12 frames with and without FRP respectively.

Response modification factor (R) values have been 3.67 and 3.46, 4.29 and 3.19, and 9.46 and 6.1 for 3, 6, and 12 story with and without FRP respectively. Ductility factor (μ) values have been 2.47 and 2.36, 3.0 and 2.43, and 5.93 and 4.27 for 3, 6, and 12 story with and without FRP respectively. Based on using FRP, response modification factor and ductility have been improved by about 5.7%, 25.5%, and 35.5% for R-factor and about 4.5%, 19%, and 28% for ductility for 3, 6, and 12 story respectively. In this research, the results show a significant improvement in structural behaviors under seismic loads for 12 story building with FRP better than other buildings without FRP. The effective of retrofitting by FRP in high building better than others ones maybe one of the reasons for this the complexity of the behavior of high-rise structures over short-range structures and the effect of higher modes on high-rise structures. Therefore, the higher ductility factor has represented the amount of energy of earthquake that will be dissipated and the performance of structure will be in safe zone.

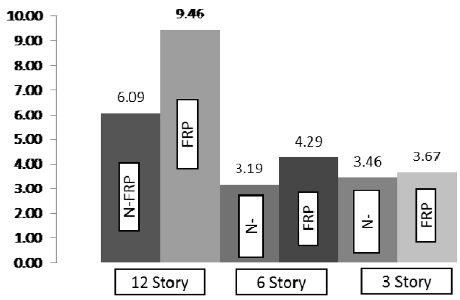


Fig. 5. Comparative between R-factor for different frames with and without FRP

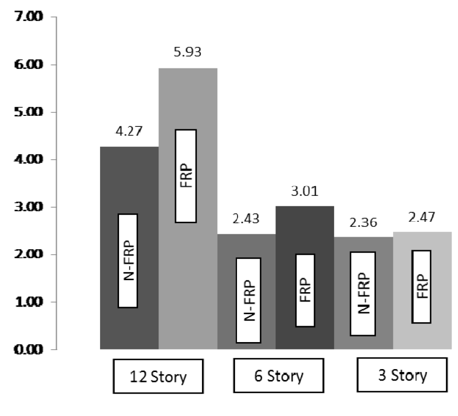


Fig. 6. Comparative between ductility factor for different frames with and without FRP

VI. Conclusion

Use FRP plates and strips are not only useful as a repair tool to recover a beam section's lost strength but are also very successful in reinforcing concrete structures to withstand additional loads. FRP increases the strength and service life of RC beams and increase the fatigue efficiency of the strengthened beams. The beam's failure, mostly impacted by fracture of main-reinforcing bars.

According to the results and due to push-over analysis, response modification factor (R) values have been 3.67 and 3.46, 4.29 and 3.19, and 9.46 and 6.1 for 3, 6, and 12 story with and without FRP respectively. Based on using FRP, response modification factor has been improved by about 5.7%, 25.5%, and 35.5% for 3, 6, and 12 story respectively. Ductility factor (μ) values have been 2.47 and 2.36, 3.0 and 2.43, and 5.93 and 4.27 for 3, 6, and 12 story with and without FRP respectively. Using FRP has enhanced ductility factor by about 4.5%, 19%, and 28% for 3, 6, and 12 story respectively. The results show a significant improvement in structural behaviors under seismic loads for 12 story building with FRP better than other buildings without FRP. The higher ductility factor has represented the amount of energy of earthquake that will be dissipated and performance of structure will be in safe zone. The effective of retrofitting by FRP in high building better than others ones maybe one of the reasons for this the complexity of the behavior of high-rise structures over short-range structures and the effect of higher modes on high-rise structures.

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Polypropylene Fibers to Resist Concrete Spalling Caused by Fire

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Abstract:
In fast-heated concrete the explosive behavior of concrete is observed in fire. The key factors regulating the spalling phenomenon are attributable to the low porosity and high density of the material, as well as the restricted capacity to move gases and liquids. Therefore the chance of spalling is much higher for high-strength, ultra-high-strength, and reactive powder concrete than for concrete with normal-strength. This paper provides a description of explosive concrete spalling at explosion. An area of engineering design, implementation, and study that produces contradictory theoretical and practical advice is the use of polypropylene fibers in concrete to prevent explosive spalling in the event of an explosion. This study offers a thorough analysis of the many considerations that need to be addressed in the design of a fiber-reinforced shotcrete and in-situ concrete to satisfy not only the customer's requirements for cost-effective construction, but also the requirements of the engineer for guaranteed optimal resistance to explosive spilling and the contractor's all important ability to easily mix and position the concrete, on time and by definition. Fiber forms, dosage, efficiency and safety margins, mixing and distribution are studied, and the impact on concrete properties.

***Keywords:** Fire, Temperature, Concrete Spalling, Polypropylene Fiber, Spalling.*

1. Introduction

For several years Concrete has been the main building material and the impact of fire on concrete has been studied for a long time. It is likely that during a explosion, concrete, which is an incombustible material [1], will act explosively due to the spalling phenomenon. Spalling is described a sudden, violent or non-violent loss of concrete cover [2, 3]. Spalling actions can jeopardize concrete components' load-bearing ability due to conservative cross-section loss and reveal steel reinforcement vulnerable to can temperatures [4]. This can lead, in a burn, to a decrease in the ability of the product and even to its collapse [5]. Since the effects of fire in concrete structures can be very serious, a series of studies have been carried out to find ways of minimizing concrete tendency to spall due to exposure to fire [6–9]. It was found that the addition of polypropylene fibers (PP) to the concrete mix would offer positive results. The polypropylene fibers in concrete do not change their mechanical and physical properties at normal temperatures significantly [10]. Nevertheless, as the temperature increases due to heat, the fiber-free concrete permeability increases at 200 C as much as 50 times compared to the fiber-free concrete [11]. A network of pores is formed as fibers melt that increases the permeability of the concrete. This allows the transportation of vapour, reduces the pressure of vapour, and minimizes the risk of concrete spalling in fire.

This severe damage indicated that while the strength and durability of high resistance concrete is considerably higher than that of traditional concrete mixes (offering better mechanical properties, low porosity and chemical resistance), because of its high density and susceptibility to high pore pressures and internal tensile stresses, it is much more prone to fire harm. The severity of this destruction has raised major concerns about the survival and structural stability of tunnel lines following a possible fire and has triggered much field work [12, 13].

Ultra-high-performance concrete is an unnaturally synthetic substance low in water-cement ratio and high in strength, impermeability, density, and fragility. In the event of an explosion, these characteristics make it easy to break, resulting in a decrease in power. The application of polypropylene fibers not only helps increase the strength and elasticity of the concrete, but also creates breathing vessels as the ambient temperature increases. Despite these advantages, ultra-high-performance fiber concrete can withstand heat and pressure for a fairly long period without getting seriously hurt, thereby giving firefighters period to save human lives and property [14 - 16].

To reduce brittleness fiber is added to the concrete [17- 19]. The fibers enhance concrete ductility and mechanical strength [20, 21], minimize plastic shrinking and improve resistance to room temperature effects [22, 23].

2. Spilling into various concrete types

2.1 High performance concrete (HPC)

The high compactness of HPC is the key parameter liable for spalling at high temperatures as per [24]. When contrasting empirically a normal concrete (M30, w / c=0.5) with an HPC concrete (M100, w / c=0.32), both with calcareous aggregates, it could be found that they have a similar thermal activity globally, due to their comparable insulate properties (thermal conductivity and heat). The distinction comes in the calculation of the pore pressure, in the HPC up to 38 bars and in the standard concrete 18 bars; HPC also experienced higher pressure vectors than the standard concrete.

It can be seen that as a result of lower permeability (to vapor and water vapour), there is a substantial difference in the thermodynamic conditions encountered in the transparent system, resulting in a much greater membrane pressure.

2.2 High strength concrete (HSC)

Tests carried out on HSC by [25] were performed on 16 samples, 12 with mixtures of silica fume, and 4 without. It has been noted that all the samples of mixtures heated above 300 C have undergone a form of spalling and lack of mass. In the experiments, spalling varied from negligible aggregate spalling (which induces surface pitting) to, in severe cases, large portions of the samples being burst 800 °C with destructive force that are classified into four types: explosion (parts greater than 1 cm), surface (parts less than 1 cm), aggregate and corner spalling.

The tests revealed that the level of spalling significantly decreased when the amount of water to binder ratio rose in mixes including silica fume and also that silica fume could generally regulate destructive spalling caused by increased tensile resistance.

2.3 Self-Compacting concrete (SCC)

Tests performed on SCC by [26] found that destructive spalling exists in both pulsated concrete and SCC at a range of temperatures from 350 ° C to 580 ° C. At the other hand, no spalling was found on any of the specimens examined for LSCC (Laterized Self Compacting Concrete). There was no crack detected at up to 600 ° C in LSCC. Also at 800 ° C surface fractures were observed on the samples, and the amount of cracks in water-cooled samples was greater.

Understanding concrete spalling

Spalling can be divided into four classifications: (1) aggregate spalling; (2) destructive spalling; (3) spalling of surfaces, and (4) spalling of the corners. The first three happen in a fire within the first 20-30 min and are affected by the level of heat, whereas the fourth happens after 30-60 minutes of flame and is affected by the high temperature. It can also be claimed that ground spalling is actually a type of explosive spalling which is the most dangerous spalling type [27].

Concrete spalling could be defined as fracturing off sheets or parts of concrete from a structural element's surface when exposed and rapidly growing fire temperatures [28]. Three different types of spalling concrete are:

Surface spalling: During the early part of the explosion, small pieces of concrete, up to 20 mm in size, are slowly and non-violently dislocated from the earth. This is usually caused by splitting of the composite fragments at high temperatures due to physical or chemical changes. The deterioration of the concrete in surface spalling is fairly slow and requires oxidation of the cement matrix accompanied by the lack of connection among aggregate and matrix. If the temperature increase is slow, there is time for the moisture in the concrete to move from the exposed side to heat, and there is limited pressure build up. In this situation, the presence of moisture will help reduce the impact of the increase in temperature, because much energy is expended in converting moisture into vapour.

Corner break-off: Also recognized as skin peeling off, when the concrete has fractured and collapsed, corner break-off occurs at the edges and corners of concrete structures during the latter phases of the burn.

Explosive spalling: Undoubtedly the most extreme and harmful type of spalling that happens within the first 20–30 min of a flame when the concrete temperature is within 150-250 ° C. Combustible spalling happens as the temperature increases exponentially, such as in fires fueled by hydrocarbons after a traffic crash, where very pieces of concrete can be thrown aggressively for many meters. When a fresh concrete mask is exposed to the flame radical destructive pouring happens deep into the concrete surface, undermining the construction's structural stability.

It is recognized after many decades of study that there is a complex mix of chemical, physical, and thermodynamic factors that affect the spalling of explosives. Which include humidity content, aggregate form and thickness, concrete permeability, warming capacity, reinforcement presence, and exterior loadings. Scientists agree that when high strength, low permeability concrete is specified, there is a substantially higher chance of explosive spalling due to the larger pore pressures that accumulate throughout warming.

The hypotheses about how and why destructive spalling happens are primarily moisture dependent. If the concrete temperature rises, the concrete humidity transitions to steam vapour. This vapor causes a dramatic rise in the pressure within the concrete if it is unable to escape. As this cycle progresses, the strength of the vapor increases to the point that it exceeds the concrete's tensile capacity, causing violent and explosive dislodging of concrete parts. Besides this modern theory of 'moisture movement,' there is an agreement that aggregate contraction induced by thermal stresses often directly affects destructive spalling.

Why polypropylene fibers avoid explosive spills

The application of appropriate polypropylene nylon microfibers (Figure 1) to counteract incendiary spalling in cast concrete [29] and shotcrete [30] has been recognized for several years, but it is important to have an awareness of the thorough mechanism by which these fibers function in order to develop an engineered microfibre to avoid explosive spalling. Because the spalling is induced by pressure caused by a limitation on moisture or steam movement, then the presence of the fibers must alleviate the pressure somehow.

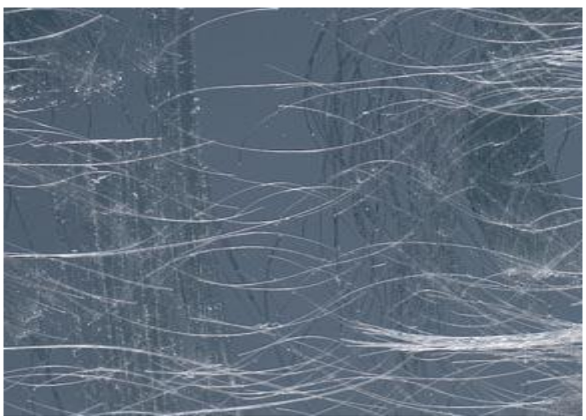

Figure 1. Monofilament polypropylene fibres (PP)

As the heat in reinforced concrete increases in the microfibre, the PP softens and starts to melt due to a gradual phase shift that starts at around 150 ° C where the crystallinity starts to break into an undifferentiated polymer. It rises at 165 ° C (the widely known boiling point), and is full at around 175 ° C. It's this melt that is presumed to promote the decrease in the concrete's internal stresses which cause the destructive spalling. There are two key hypotheses on how these microfibers do it.

Mechanisms: While acknowledging the probability of other processes, Khoury [31] supports what he calls a PITS (Pressure Induced Tangential Space) concept in which the steam supersedes the PP's contraction as it melted, squeezing between the microfiber and the concrete matrix and moving along the fiber duration. He argues that the efficacy of such a system would rely on the microfibre's accumulated land area and fiber communication, and is therefore favored by an ultrafine fiber with a diameter of around 18μm which offers a very large number of fibres. Because microfibers are scattered across the concrete, how the connection of the fibers is generated as well as how the steam pressure is alleviated is not clear. This hypothesis is also unable to understand why microfibers with a diameter of 32μm-which have just one third of the number of fibers relative to 18μm in diameter-have proved to have equivalent and probably slightly superior destructive spalling resistance [32].

Microcracking mechanism: An alternative hypothesis proposed by [33] argues that its much higher frictional heating coefficient compared with that of concrete (8.5x) produces a huge number of microcracks when an individual PP fiber melts. Such newly formed microcracks will then attach to the microcracks formed by the thermal expansion of adjacent microfibers, or by heat triggered stresses, to form an interlinking system that can promote the flow of steam through concrete. It was this permeability that is only generated if a fire event happens, which relieves the stresses generated by the steam generator and mitigates the risk of destructive spalling.

Liu et al [34] discovered from back scattering electron microscopy (BSE) and gas permeability monitoring that the melt of PP fibers improved the functionality of the insular pores resulting in increased permeability, with maximum permeability happening at roughly 200 ° C or shortly after polypropylene boiling point. It was established that the formation of microcracks and their access to a system (Figure 2) are important determinants concrete's permeability when exposed temperatures.

Figure 2. Microcracking network

Saka et al [35] notes from preliminary finite element analysis experiments that a single PP fiber inserted in a mortar matrix and subject to an increase in temperature of 140 ° C induces considerable stress on the framework because of disparity in the frictional heating coefficients. Khoury [31] also suggests that the large gap in thermal expansion among concrete and PP polymer leading to the creation of microcracks exerts a substantial tensile stress on the underlying matrix.

In concrete, microcracks are often formed by thermal gradients such as aggregate contraction, drying shrinkage and producing steam. But, it is the additional development of microcracks created by the melt of the PP microfibers that occurs with these holes and interfacial transition zones in a habitual / national system [36], which offers the highest degree of concrete security towards destructive spalling.

The greater the weight of the single fibre, the greater the tension that the melted polymer will produce and the enhanced propensity to form microcracks as a consequence of that tension. However, very large a single fiber results in a smaller number of fibers spread in the ground, which limits the possibility of channel creation. Likewise, at other end, so tiny an actual fiber increases the potential for microcracks to form, limiting the system that can be generated, thus reducing the overall fiber's ability to avoid destructive spread. [37]. Between such two poles exists the optimum fiber size for the most effective explosives resistance to spalling.

Optimum fibre dimensions: Jansson and Boström's research [37] contrasted the output of 12 mm long PP microfibers of two specific diameters (32 μm and 18 μm) in test boards made from concrete commonly used during tunnel building in Sweden. The experiments were performed under circumstances designed to promote a propensity for destructive spalling, like: using a more intense Rijkswaterstatt (RWS) fire curve of 2 hours at a peak temperature of 1.350 ° C against the regular Eurocode 1 fire curve of 1.100 ° C for 2 hours (Efnarc, 2006), use large panels of 1.200 mm x 1.700 mm x 300 mm instead of small panels of 500 mm x 600 mm x 300 mm, using large aggregate versus smaller aggregate, and testing panels with high moisture content under compressive load and with low fibre dosages (Figure 3).

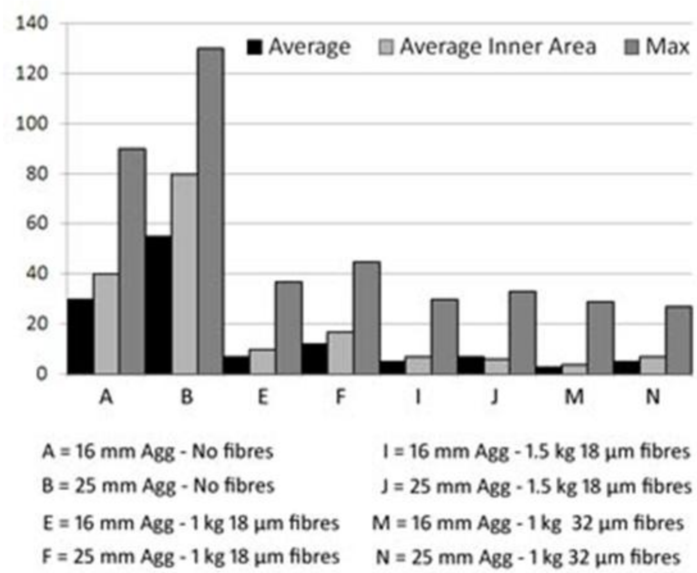

Figure 3. Spalling depths (mm) of large scale slabs after 30 minute fire exposure to RWS fire curve.

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The figure 3 clearly, evidence invalidates the idea that it is actually the amount of fibers in the concrete that defines the efficacy of the fiber provide destructive resistance to spalling. Because it is seen that the PP fibers with a diameter of 32µm have at least comparable output to 18µm diameter fibers, which are 3.2 times more frequent in concrete. The results also show that panel comprising 1.0kg / m3 of 32µm diameter fiber produced slightly better outcomes than those comprising the 18µm diameter fiber higher dose of 1.5kg / m3. The number of fibers in the concrete is a success factor but obviously it's not the major factor.

Together with in-house work at propex concrete systems in poured concrete and shotcrete [38], this research supports Sullivan and others' view that it is the extension of the melted PP fiber that causes the microcracks to build a channel for steam pressure relief; This is the predominant mechanism for the provision of destructive concrete spilling resistance. The important requirement is that the microcracks have to be generated before any system can exploit the pressure alleviating benefits. By using a 32µm diameter fiber rather than a smaller diameter fiber, including an 18µm diameter fiber, this process is preferred.

Similarly, a fiber of 12 mm length will increase the amount of individual fibers and encourage the development of microcracks in a fire, more than a 6 mm long fiber, while also providing adequate numbers of fibers (approx. 120 million / kg) will create the system needed to dissipate steam vapour. While a 6 mm fiber will function at a high level, a 12 mm fiber would be more efficient, especially under serious conditions where the highest performance degree is needed and discrepancies between fibers can be seen. In contrast to the length of the fiber diameter, there are other essential criteria to integrate fibers into concrete to achieve a functional, viable fiber to avoid destructive spalling.

For example, the various parties concerned can have different demands. The consumer needs a fire-resistant, robust structure, quick installation, minimal servicing repairs, low service loss during repair, decreased insurance rates and a price-effective solution. The designer / engineer needs approved potential for destructive spalling resistance, performance guaranteed materials, no adverse effects on other concrete assets, ease of use in building and an efficient solution. The technician / concrete manufacturer needs a cost-effective approach, ease of adding to concrete, and no issues about mixing and concrete delivery. Obviously, the overall best requirement would be a fiber that offers the optimal balance among established explosive spalling resistance, convenience (trouble-free use) and cost-effectiveness – a fiber that meets all of the stakeholder needs.

PP microfibers are compliant with steel fibers and chemical admixtures, combining, distributing, pouring and casting / wet spraying close to unreinforced concrete / shotcrete. The fine quality of PP fibres has been noticed not to be consistent with the dry shotcrete framework [30].

Practical considerations: There have been many instances of works where fibers have been solely chosen for spalling outcomes from tiny-scale lab testing and then, when complete-scale site development has started, engineers and contractors have seen that certain fiber materials have a significantly negative effect on the concrete-especially the workability, air quality and compressive strength. Adjustments to the mix configuration were then made to counteract these negative results, and the fire test data were essentially made void. Thus, it is important that designers take into account the impact of the

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fibers on concrete workability, air quality, and strength during selection for PP microfibres.

Effect on workability: The effectiveness of all fiber reinforcing depends on achieving a uniform fiber distribution throughout the concrete, its contact with the cement matrix, and the capacity of the concrete to cast or spray effectively. Basically, to have some value in the concrete, each single fiber needs to be covered with cement paste. Users of fiber reinforced concrete will understand that adding more fibers to concrete, especially with a very limited diameter, would have a larger negative impact on workability and the need for improvements in the design of mixtures. Because the average surface area of very small diameter fibers is much higher (for example, 18μm diameter fibers have a surface area 77 per cent greater than 32μm diameter fibres). This additional demand on the cement paste, unless changed by adding more water and cement or alloying elements (and thus the costs), would ultimately have a drastic impact on the concrete's workability, especially if the dose is above 1kg/m3. Kompen [39] recorded Norway experience that ultrafine fibers in wet shotcrete have an impact on the mix's water request and that the fibers were extracted from the shotcrete filters and jammed air filters on the spray machines.

Effect on air content: A practical thing to consider in the choice of PP microfibers is that it is more difficult to disperse packets of very small diameter fibers in the concrete, and it is known to carry more air into the concrete. Relative site tests have shown that the higher air content for concrete with 18μm diameter fibers was about 5-8 percent opposed to about 1.0 percent for a fiber with a diameter of 32μm. This rise has a negative impact on concrete strength which in basement structures is not attractive. Few works using 18μm diameter fibers have made use of deforming products to reduce the air content. This will ultimately affect the concrete's in-place costs and put a period on the validity of any fire tests conducted to determine the destructive spalling efficiency of the initial concrete / fibre mix.

The use of ultrafine microfibers will result in a very loss of concrete strength with a 6 percent reduction in compressive strength for every 1 percent increase in air content. In an attempt to divert focus from the adverse effects these very fine diameter fibers have on workability and air quality, it was proposed that lower dosages be the solution. Although this may be viewed as an fascinating commercial strategy for contractors and ready-mixed concrete suppliers whose goal is to provide a lower cost solution, this recommendation increases the level of destructive spalling resistance and should not be endorsed on the grounds of tiny panel lab testing of concrete with elevated air volume. This rise in air content does not present a shotcrete issue as the air is forced during blasting, but if the fiber output for a shotcrete mix is measured on a cast concrete stand, The raised air content that cover the fiber's coaching ability to overcome incendiary spalling when used in the actual shotcrete as it enhances the likelihood of completing a fire test concrete board.

Addition and mixing of PP fibres: Adding PP monofilament microfibers to concrete is a fairly simple method which depends on the project size. Normally, fibers specially designed for concrete reinforcing are supplied in entirely recyclable paper wrapping, which allows the required dose per unit volume to be easily applied directly to the concrete truck or pan mix. The wrapping is meant to break down easily, enabling the fibers to be evenly spread through the concrete. This is also the most efficient approach to implement in comparatively small ventures, with labeling accessible in 1 kg bags or 2 kg bags.

Where works require substantial amounts of PP microfibres, contractors and ready mixed suppliers

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frequently suggest using more advanced, standardized ways of applying fibers to the concrete. Fiber dose machines maintain an accurate measurement and automatic delivery to the concrete mixer of the appropriate amount of fibres. While using very fine fibres, they risk sticking together in packets, being coated in cement paste and not uniformly spread in the concrete. This was see during fibre washing out experiments when fiber clumps were found. This is clearly inappropriate as security towards destructive spalling is not distributed evenly in the concrete. This was not a concern with the fibers with a diameter of 32µm, which also performed well in automated fiber administering and distribution systems.

3. Fibers role

As per [40], the inclusion of long fibers (lf > 10 mm) has a structural-level effect, which helps to increase the material's deformability. Fibers are slowly employed shortly after cracking, resulting in a multi-cracking cycle (pseudo-hardening phase) and crack translation (softening behaviour).At the other hand, the introduction of short and microfibers (a few mm long) has an effect on the level of the material, helping to increase the tensile strength correlated with the pseudo-elastic domain. Instantly after concrete microcracking the microfibers are enabled, contributing to a concrete behavior defined by a longer elastic period (elastic + pseudo-elastic).Owing to their high strength, high resistance in alkaline environment and high elasticity modulus, steel fibers (twisted, hooked-end, straight long and short) are used regularly in UHPFRC mixtures.It really is worth noting that in a fire situation, polypropylene fibers (PP) can be inserted into the concrete mix to prevent destructive spalling. In this case, melt of PP fibers, about 180oC, results in an increase in permeability, removing the vapor pressure within the matrix.The different types of fibers are shown in Figure 4.

Figure 4. Synthetic and steel fibers used in concrete formulations

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3.1Orientation and alignment of fibres

The size of the sample, boundary conditions (wall effect), mixture workability, fiber thickness and compaction procedures affect the distribution and alignment of fibres.Experimental experiments carried out on round panels[41] using X-ray computed tomography and tests of electrical resistivity showed that the better results in terms of strength capability were obtained by pouring concrete from the core.The movement of concrete inward from the middle of the panel contributed to the fibers being preferentially aligned, parallel to the panel length, expanding the number of fibers trying to bridge the cracks.

4. CONCLUSION

- High temperature penetration contributes to a marked reduction in UHPC's mechanical properties due to physical-chemical transformations (free water evaporation, CSH dehydration, and microcracking). In addition, despite its compact microstructure, UHPC is susceptible to violent spalling. Research on this region has shown that a small amount of PP fibers integrated in the mix can reduce spalling triggering and even avoid it.

- The introduction of polypropylene fibers has proven to be an amazing method for minimizing the explosive spalling of RPC when subjected to temperatures of up to 800 ° C due to the melting of polypropylene fibers and instead leaving vacuum for vapor injection.

- If fibers are to be used to provide explosive spreading resistance in shotcrete or cast in-place concrete, two key requirements should be met: a proven ability to withstand explosive spalling along with no adverse side effects in concrete. The best way to meet these requirements was to use a fiber made of 32µm diameter and 12 mm long polypropylene monofilament manufactured to and in line with ISO 9001 and EN14889-2 specifications.

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