Study on Exposure of Reinforcing Bars and Concrete Exposed to Fire – A Review

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Abstract— In this modern era, most of the buildings all over the world are made up of RCC. The increasing incidents of fire in buildings have increased the importance of assessment; repairs and rehabilitation of such buildings as these buildings are very costly. This field needs special expertise in many areas viz. concrete technology, structural engineering, material testing, and repairs and maintenance etc. A continuous effort through research and development programmes all over the world is being made in this specialized field. This topic gives us immense pleasure as we deal with the real life problems in this research. In this research, we gain the knowledge which is being used as a strategy for the rehabilitation of fire damaged buildings and by conducting proper assessment procedures by non-destructive techniques. In this research, we did various experiments so as to find out the effect of fire on the reinforcing bars in RCC buildings by taking 6 samples at 110°, 310°,610°,900° each for 3 hours. After heating the samples, they are cooled quickly by quenching in water and normally by air cooling. It is seen that there is a change in the mechanical properties of samples which are studied under universal testing machine (UTM) and for close look at reinforcing bars in a fire damaged structure, scanning electron microscope (SEM) is used. From conclusions, it is seen that most of the fire damaged RCC are restorable. The mechanical properties of all common building materials decrease with the elevation of temperature. The behavior of a RCC in fire conditions is governed by properties of constituent materials, concrete and steel at high temperature. Both concrete and steel undergo considerable change in their strength, physical properties, and stiffness by the effects of heating. It is also seen that above 900°C some of these changes are not recoverable after subsequent cooling.

Keywords: Reinforcing Bars, Fire, universal testing machine (UTM), scanning electron microscope (SEM)

I. Introduction

In this modern era, most of the buildings all over the world are made up of RCC. The increasing incidents of fire in buildings have increased the importance of assessment; repairs and rehabilitation of such buildings as these buildings are very costly. This field needs special expertise in many areas viz. concrete technology, structural engineering, material testing, and repairs and maintenance etc. A continuous effort through research and development programmes all over the world is being made in this specialized field. As there can be fire in any type of structure but because of this, such type of structures cannot be ignored. For rehabilitation of such type of structures after fire to make them structurally functional, it has given civil engineers a tough challenge. Firstly civil engineers have to find the amount of damage caused to the structure by the fire. The difficulty starts from where to start the rehabilitation work and how to work on such type of structures. It is, therefore, important to build such type of structures that are efficient enough to prevent the loss of life as well as property. Annual statics regarding fire showing loss in residential buildings, offices, industries etc can be used for the development of fire safety design.

As we know that damages due to fire can lead to loss of human life, property and livelihood. As per the World Fire Statistics 2018, a survey of 14 industrialized countries (12 in Europe, USA, Canada and Japan) found that, the human lives lost due to fire in a typical year amounted to about 1.5% to 2.6% per 1,00,000 inhabitants and the total damage of property amounted to 0.3% to 0.4% of Gross National Income (GNI). As per the National Fire Protection Association (NFPA's) statistical data about USA for the year 2017 showed that United States fire departments responded to an estimated 1,219,500 fires in 2017.These fires resulted in 3,350 civilian fire fatalities, 13,670 civilian fire injuries and an estimated $22 billion in direct property loss. Fire Fatalities UK showed that fire deaths in England increased sharply last year. There were 335 fire deaths in England (including 71 at Grenfell). This is the worst year for fire deaths since 2010-2011. Fire-related fatalities in England rose by a quarter between 2016-17 and 2017-18 from 260 to 330.The amount of damage caused by fire in a RCC structure depends on a number of factors such as structural design and performance aspects, fire fighting equipments and evacuation plans provided in a building. Fire safety standards like working fire alarms, fire extinguishers, proper ingress and egress, hazardous materials, flammable material storage and maximum occupancy are important for the safety of people in case of fire in a building. They assume greater importance. For the fire safety construction, it is necessary to have proper design and choice of materials. Codes and Regulations on fire safety in buildings should be updated from time to time through conducting proper research and development.

Pietro Croce (2001) developed a method which is illustrated for assessing the fire damage occurred to the RCC buildings. For close look of reinforcing bars in a fire damaged structure is investigated by Wei Lin (2006) by using Scanning Electron Microscope (SEM) and Stereoscopic or Dissecting microscope for concrete by heating it to a temperature of about 950°C to get good visualization of concrete to understand the behaviour of concrete in fire which would have been impossible with the naked eye. Post fire curing effect on the strength and durability recovery was investigated by Chi Sun Poon (2001). M.A.Riley from Sir William Halerow and Partners (1991) has given "Possible new methods for assessment of fire damaged buildings". Assessment of fire damaged structures by using colour image analysis by

N.R. Short. The effects of rapid cooling by water quenching on the stiffness properties of fire-damaged concrete was studied by A. Y Nassif of London University in the year 1999.

II. CHANGES DUE TO FIRE IN RCC STRUCTURES.

The various changes which arises due to fire in a RCC structures are given below

1) Among all fire damaged structures, most of them were repairable and remaining which are not repairable were demolished for their unsafe reason for people.
2) Most of the structures performed well during and after the fire except few structures.

It gives rise to various problems in a RCC structure like

- Damage in structural members.
- Excessive loading.
- Seismic damage.
- Structural cracks
- Error in design or construction

Fig. 1.1: Fire Damaged Slab

Fig. 1.2: Concreting of Fire Damaged Slab

III. EFFECT OF FIRE ON CONCRETE

The properties of concrete changes suddenly when exposed to high temperature, many problems were experienced with concrete in fire like change in mechanical properties. Rise in temperature due to fire up to 90°C have little effect on the strength and other properties of concrete in a structure. Failure of concrete in a structure due to fire depends upon the type of structure, loading system and nature of fire. Reason of failure could be from loss of bending strength; loss of compressive strength and spalling of concrete.

Fig. 1.3: Concrete against Fire

IV. PHYSIOCHEMICAL CHANGES IN CONCRETE UNDER FIRE.

Concrete is basic primary material used in the construction of a structure having important advantages like strength, simple fabrication, non-combustible properties and durability. Structural member made of concrete used in a building construction have to satisfy Fire Safety Standards specified in Building Code. Provision for fire safety measures is an important aspect for the safe design of a building. Fire safety measures in a structural building are measured in terms of resistance offered against fire by a structure during which it resists structural integrity, durability and heat transmission. Concrete has the best fire resistance properties of any building material used in the construction process. Concrete with its main constituents cement and aggregates which, when mixed form a inert material having low thermal conductivity, slow heat transfer and slow loss of strength with increase of temperature which enables concrete to act as an effective fire shield to protect itself from fire damage. The fire resistance of a concrete in a structure mainly depends upon mechanical and deformation properties of concrete of which it is made of. The mechanical and deformation properties of concrete changes with substantial increase in temperature. These properties vary as a function of temperature. They also depend upon on concrete composition and its characteristics. The High Strength Concrete (HSC) and Normal Strength Concrete (NSC) show different variation with temperature in their properties. The variation is more noticeable in mechanical properties rather in deformation properties. These properties are affected by strength, durability, moisture content, rate of hydration and porosity.

Fire resistance of concrete in a member, in practice, is mainly done by Standard Fire tests. But numerical methods have also gained importance in recent years for the calculation of fire resistance because these methods are very less costly and less time consuming. A standard fire test on specimen (Deep beam) of area 150mm × 150mm and 400 mm deep concrete beams shows that when three sides are exposed for 50 minutes, a temperature of 650°C reaches at a distance of 18mm from the surface and this value halves itself to about 325°C at 40 mm from the surface. Even for a long period of time, the internal temperature of concrete does not rise too much and remains relatively very low, which provides stability, durability and fire resistance to the structure.

The external appearance of a concrete member shows the affect of heat to which these members have been subjected during the fire. The external appearance as observed gives us information regarding the physical condition of a concrete member and also gives us idea to access the approximate damage caused to the member. The above information plays a vital role in providing basis for damage classification and proper techniques for repairing. The above information is subjective and therefore, the result would depend on the past experience of the observer carrying the investigations. The information received from the surface experience combined with other methods provides a valuable tool regarding decisions being taken on the repair methods to be carried out.

Temperature (°C)	What happens
1000	
900	Air temperatures in fires rarely exceed this level, but flame temperatures can rise to 1200°C and beyond.
800	
700	
600	Above this temperature, concrete is not functioning at its full structural capacity.
550-600	Cement-based materials experience considerable creep and lose their loadbearing capacity.
400	
300	Strength loss starts, but in reality only the first few centimetres of concrete exposed to a fire will get any hotter than this, and internally the temperature is well below this.
250-420	Some spalling may take place, with pieces of concrete breaking away from the surface.

Table 1.1: Colour Change in Concrete at Elevated Temperatures

The various problems covered above are discussed briefly below.

A. *Plastering and Finishing:*

The minimum requirements of gypsum or Portland cement plaster used in fire resisting buildings should be determined by fire tests. For this purpose 3/4inch or 19.1mm of plastering of such material should be done. In buildings of type II and Type III construction, plaster should be applied directly on the concrete or mortar. On the plastering, there should be a finishing layer which acts as a fire insulating material.

B. *Colour:*

The concrete may change its colour as a result of heat due to the fire in a structure and gives us idea about the maximum temperature attained in a concrete structure. Generally, concrete made from calcareous aggregates changes its colour to red. The reason for the same is that the iron present in calcareous aggregate dehydrates due to high temperature. The possible colour change is normal pink, whitish grey and puff.

Heating temperature	Stone type			
	Limestone	Sandstone	Marble	Granite
250°C-300°C	Pink or reddish brown discoloration starts at 250°C- 300°C but may not become visible until 400°C	Red discoloration starts at 250°C-300°C but may not become visible until 400°C	Heating marble through a range of temperatures causes a non- reversible expansion known as thermal hysteresis	-
400°C	Discoloration becomes more reddish at 400°C	-	-	At less than 573°C, if heating rate is less than 1°C per minute the Thermal expansion is fully reversible and if thermal expansion is more than 5°C per minute Thermal expansion is not Totally reversible.

600°C	Calcination of calcium Carbonate commences at 600°C	Heating above 573°C causes internal rupturing of quartz	Above 600°C complete disruption due to differential expansion	Develop cracks due to quartz Expansion

Table 1.2: Changes Caused By Heating Various Types of Stone

C. Crazing:

Crazing is a phenomenon which produces network of fine cracks on the concrete surface due to sudden cooling of surface by applying water on the fire. These fine cracks can go up to 4mm deep. It is also known as Map cracking or Alligator cracking. All the crazing cannot be removed but, the development of fine cracks on the surface of the concrete can be removed by applying polish on the surface. It does not affect the strength of concrete.

D. Spalling of Concrete:

Spalling is the breakaway of concrete surface from the concrete member due to the result of water entering the concrete. Spalling happens due to the presence of moisture present in concrete. It generally happens to old buildings. Due to spalling, reinforcing bars gets exposed to atmospheric moisture which in turn reduces the strength, durability and stiffness of the structural member. So, as soon as spalling is spotted, it should be properly repaired otherwise it compromises with concrete surface integrity.

Remedies for spalling vary by the severity of the problem, the type and location of concrete structure, and other factors.

- When the spalling damage is shallower than 1/3 of the concrete's thickness, the concrete usually can receive a surface repair. If the damage is greater than 1/3 of the depth, steel bars may need to be installed and a full depth restoration may be required.
- Corroded rebar, due to exposure, must be cleaned at the beginning of the restoration process. Once the rebar is thoroughly cleaned (usually with a wire brush) and all corrosion is removed, the rebar should receive a protective coating of rust inhibitor to minimize future corrosion.
- Damage on driveways, walkways, and other horizontal surfaces may be repaired with a cementitious overlay. After the overlay has set completely, a waterproofing membrane should be applied to prevent spalling from recurring.
- Patching may be a repair option for random or localized damage. Patches should extend at least 4 inches beyond the spalled areas. For best results, the surface can be saw-cut in the patch area to help contain and secure the patch.
- Surfaces to be patched should be free of all debris and fine particles and should be completely dry before patching material is applied. It's best if the old concrete surface is rough to provide tooth for better bonding. The best patching materials are Portland-cement-based or epoxy and should be mixed immediately prior to application, as directed by the manufacturer.
- The air temperature must be over 40 F for patching or other restoration work to ensure proper bonding and curing of the repair material.
- Repair materials should have an expansion coefficient similar to that of the original concrete.
- Any joints that are repaired must allow for expansion of the concrete slab.

Fig. 1.4: Spalling of Concrete due to Fire

E. Exposure conditions of reinforcement and concrete:

The environment to which the concrete will be exposed during its working life is called exposure conditions. The exposure conditions are classified as mild exposure, moderate exposure and high exposure. The exposure condition of main reinforcement and distribution reinforcement are classified in the spreadsheet as 25%, 50% and 75% with the indication of buckling of main reinforcement.

F. Cracks:

Cracks develop when concrete members in a structure gets exposed to high temperature. These cracks may develop across the concrete member due to the following reasons.

- It may be due to expanding and shrinking of concrete due to temperature difference.
- It may be due to settlement of structure.
- It may be due to application of heavy loads.
- It may be due to corrosion of reinforcing bars.
- It may be due to improper cover provided.

G. Distortion:

The distortion arises in the concrete member due to temperature in the form of deformations like twisting, deflections etc. They may be recorded in the spreadsheet as none, slight but insignificant and severe but significant.

H. Delamination of concrete:

Delamination of concrete may be defined as the detachment of thin layers of concrete from the concrete member. It can be detected by tapping the concrete surface by light hammer. If dull sound is heard indicates the presence of delamination. In the spreadsheet, it is indicated by the surface area to be recorded.

Some of the causes of delamination of concrete are

- Use of a sticky mortar mix with huge amount of fines.

- High rate of evaporation.
- Hastily performed finishing works.
- When the finishing process is performed hastily, the delamination work would spread over the entire area.

Fig. 1.5: Delamination of Concrete 1.5: Tests to be conducted on the RCC structure.

Various tests to be conducted on a RCC structure are given below

- Non destructive field testing
  1) Rebound Hammer Test
  2) Ultrasonic Pulse Test (UPV)
  3) Electromagnetic Test
  4) Laser testing machine Test
  5) Vibration Analysis (VA) Test
  6) Core Test
- Laboratory Tests

1) Thermo gravimetric Analysis (TGA):

Thermo gravimetric analysis or thermal gravimetric analysis is an analytic method in which weight change is measured as a function of time or temperature under a controlled atmosphere. In this analysis, change in weight of a material is recorded as a function of time or temperature. Firstly, the temperature in increased at a constant rate for a known initial weight of material and changes in weight are recorded as a function of temperature at different time intervals. In this analysis, weight change is plotted against time called Thermogram. This analysis gives us idea about the stability of concrete in a given range of temperatures.

2) Differential Thermal Analysis (DTA):

It is a thermal analytic technique in which material (concrete) under study and reference are made to face identical temperature cycles (i.e. same cooling or heating) so that any temperature difference between sample under study and reference material. In Differential Thermal Analysis, differential temperature is plotted against time or temperature. The curve obtained is called DTA curve. It works on the principle that when a material is heated slowly, temperature difference denoted by Δt between the sample under study and reference sample under ideal conditions of heating or cooling is recorded continuously as a function of time or temperature, heat absorbed or heat emitted is determined.

If the process is exothermic (emission of heat), temperature of sample under study is at higher temperature than the reference material.

Δt= +ve [exothermic]

If the process is endothermic (absorption of heat), temperature of sample under is at lower temperature than the reference material.

Δt= _ve [endothermic]

3) X-Ray Diffraction (XRD):

X- ray diffraction technique is a Non Destructive Testing (NDT) method which is used to find the crystalline structure present in a concrete structure. It is a direct method, used to evaluate each phase of cement to find the performance of ordinary Portland cement. In this method, when monochromatic X-ray beam is allowed to fall on a crystal, the X-ray gets deflected to form diffraction pattern. Interface arising due to diffraction pattern gives rise to dark and bright fringes depending upon interfacing of beams. In this method, we draw the diffraction pattern of a crystal with unknown composition and then compare it with the diffraction pattern of already known patterns.

V. DAMAGE CLASSIFICATION OF STRUCTURAL MEMBERS.

On the basis of information being collected from the condition of external appearance of concrete (plastering, finishing, polishing, colour, crazing, delamination etc) and related these results with Non Destructive Tests and laboratory tests, the concrete members are classified with various types of damages. The information collected is combined with the experience of observer. The visual inspection and various tests conducted gives almost accurate conditions of fire damaged structures. As the RCC structure is made up of materials of high complexity, sometimes the results may contradict due to complexity nature of materials but this can be cleared by the experienced observer. On the basis of fire damage classification, their characteristic and repair remedies are given in the table.

VI. CRITERIA FOR DAMAGE CLASSIFICATIONS:

Class of damage	Repair Classification	Repair Requirements
Class 1	Superficial repair	For this repair, use cement mortar towelling using cement slurry bonding.
Class 2	General repair	Non-structural or minor structural repairs like restoring cover to reinforcement using cement polymer slurry as bonding layer and nominal light fabric reinforcement or using epoxy mortar over the primary coat of epoxy primer. No fabric for small patches of area less than 0.09 square metre.

Table 1.3: Damage classification criteria

Damage States	Column	Beam
S5	Crushing of core concrete at joints, relative	Crushing of concrete at supports,

	movement with respect to slab and other columns (cracks > 3 mm)	excessive deflection
S4	Diagonal/Torsional cracks in concrete core (0.5to 3 mm), opening of tie bars, bucking of longitudinal bars	Reinforcement and concrete bond is broken, cracks in the core concrete (0.5 to 3 mm), shear tie bar have failed
S3	Major portion of outer layer of concrete is spalled but core is intact except for hairline cracks (0.2 to 0.5 mm)	Major portion of outer layer of concrete is spalled but core is intact except for hairline cracks (0.2 to 0.5 mm)
S2	Visible cracks (0.1 to 0.2 mm)	Visible shear cracks (near support) or tension cracks (at bottom) (0.1 to 0.2 mm)
S1	Very fine cracks (less than 0.1 mm)	Very fine cracks (less than 0.1 mm)
S0	No observable damage	No observable damage

Table 1.4: Structural Damage Category Definition for Various Building Elements

VII. OBJECTIVES.

The present work includes;

- To access the fire damaged structures to give proper repair methods for rehabilitation of a structure.
- To study how to protect reinforcing bars used in RCC structure subjected to fire.
- To study how to increase the structural integrity of the members by increasing its strength and stiffness.
- To study how to improve the aesthetics by coating after fire destruction.
- To study changes in mechanical properties of reinforcing bars by Universal Testing Machine (UTM).
- To study the structure at micro level by Scanning Electron Microscope (SEM).

VIII. LITERATURE REVIEW

The literature review showed that there is lack of knowledge regarding the behavior of reinforcing bars and concrete of a RCC structure exposed to fire. The general features of a few selected experimental researches concerning with the mechanical properties of reinforcing bars in the present article are briefly described next.

IX. LITERATURE REVIEW ON BEHAVIOUR OF REINFORCING BARS AND CONCRETE IN RCC STRUCTURE EXPOSED TO FIRE.

IA.Fletcher, Stephen Welch, Jose'L. Torero, Richard O. Carvel, Asif Usmani (2006) has investigated that steel has higher degree of performance than concrete during a fire and the strength of steel can be found out with more accuracy. It is seen that steel reinforcement bars need to be protected from temperature above 300°C-350°C. This is due to reason that steels with low carbon content shows "blue brittleness" between temperatures of about 250°C-300°C. Reinforcing bars and concrete shows similar thermal expansion up to 450°C; however, higher temperatures will result in more expansion of steel as compared to concrete and if the temperature exceeds 750°C, the load bearing capacity of steel reinforcing bars decreases to about 20% of design value.

M.A Riley, Msc. "Possible new method for the assessment of fire damaged structures" of Sir William Halcrow and Partners (1991) has investigated that the bonding between reinforcing bars and concrete in RCC structures are evaluated at elevated temperatures. 40 modified pull-out specimen of size (100×100×300) mm3 were prepared with High Strength Concrete with Basalt aggregates and three types of fibres namely brass-coated steel fibre, hooked steel fibre and high modulus polypropylene fibre cured for 27 days at 40°C. After this, these specimens were then subjected to higher temperatures of about 300°C-700°C, whereas unheated (control) ones were left in the laboratory air. The overall results of the controlled and heat-damaged specimen, pulled out up to failure and amount of cracking of the two specimen were noted. Cubes of standard size (100×100×100) mm3 were casted, cured and heated under similar conditions to conduct compressive strength and splitting strength. The results showed reduction in residual compressive strength and steel concrete bond at high temperatures. By using fibres results in the minimization of damage in steel concrete bond at elevated temperatures and reduces damage to bond strength. Specimen incorporated with hooked steel fibres attains highest bond strength against elevated temperature, followed by those prepared with mixture of hooked steel and polypropylene, and brass coated steel fibres. Statistical models for bond stress vs free end slip and bond strength vs exposure temperature were developed. These show excellent agreement with the trend behavior of present experimental data.

S M. Allam, HMF Elbarky and AG Rabeai (2013) has investigated 'The behavior of reinforced concrete one way slabs under fire loading' which has been studied by many researchers for decades. As we know that with the increase of temperature, the slab fire resistance decreases. The reason for this is that when we expose concrete to heat, physical and chemical changes occur which leads to the loss of moisture, dehydration of cement paste and decomposition of aggregates. Due to these reasons, pore pressure increases due to evaporation of water, development of internal micro cracks and damages appear on concrete. With the increase of temperature, yield strength of steel reinforcement decreases. Also high temperature leads to spalling of concrete thereby reducing its fire resistance. Spalling of concrete is caused by its high pore pressure raised during heating. High Strength Concrete is more susceptible to this high pore pressure because of its low permeability compared to Normal Strength Concrete. Therefore, HCS has less fire resistance than NSC. The behavior of concrete slab exposed to fire is very sensible to the end restrain conditions and the stiffness. The fire resistance of one way restrained slab is generally higher than the unrestrained slabs because, compressive restrain in the surrounding structure decrease the slab thermal expansion. It is also known that cover of slabs have significant effect on the fire resistance. Codes of practice states that the temperature rise leads to degradation of strength in both concrete and steel reinforcement based on aggregate type and grade of steel.

WM Lin, TD Lin and L.J. Powers-Couche (1996) have investigated "Microstructure of fire damaged concrete". They use the results of Scanning Electron Microscope (SCM) and stereo-microscopy investigation of fire damaged concrete. Samples taken either from the concrete subjected to heating and cooled by quenching in water in the laboratory or taken from concrete exposed to fire in the field. From SEM photographs, a clear chronological pattern of failure mechanism can be visualized.

Dr. Luke A Bisby, Dr Mark F Green and Dr. Venkatesh R. Kodur (2005) have studied "Response to fire of concrete structures that incorporate FRP". Various researchers after years of investigation found that fire-reinforced polymers (FRP) used for reinforcing and strengthening of concrete structures. They are widely used to overcome the ongoing struggle against deterioration caused by fire. The application of FRP's in the field is limited to bridges where fire is not the primary consideration for design because; FRP materials are combustible and susceptible to the deterioration of mechanical and bond properties at high temperatures. There is a concern that FRP's will perform poorly in fire. This paper presents a review to investigate fire performance of FRP materials during fire.

Lateef O. Onundi, M. Ben Oumarou and Abba M. Alkali (2019) has investigated "Effects of fire on the strength of the structural members". In this, researchers' main focus was on the effect of fire on the structures due to the Boko Haram Insurgency in Maiduguri, Northern Nigeria. In this research, it was also studied to understand the effect of fire with respect to local aggregates, quenching process and proposed assessment methodology based on analytic methods applied to RCC structures subjected to fire. In this research, SEM tests were carried out with Prox scanning electron microscope for imaging and analysis to physical examine and determine the microstructure redistribution and influence on the test samples.

GA Khoury (1992) studied "the compressive strength of concrete at high temperatures". It was seen that it varies from concrete to concrete depending upon its constituents and also on the type of external loading, heating and moisture. It also experiences thermal strain and shrinkage due to heating. Excess heating of the structure results in the explosive spalling having serious consequences on the structure. Explosive spalling have two mechanisms namely thermal stress spalling and pore pressure spalling. Thermal stress spalling could be reduced by using thermally stable aggregates of low expansion, whereas latter could be reduced by the use of polypropylene fibre in the mix.

9-11 attack on the World Trade Centre New York, USA gave rise to lot of interest in the design of structures for fire resistant. Some engineers have starting using advanced analytic method for fire determination of fire growth in any area of the building and using FEM for the determination of temperature within any area by heat transfer analysis. With the help of heat transfer analysis, mechanical properties at various temperatures during the fire period can be determined.

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