IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

ANALYSIS ON SUITABILITY OF FIRE PROTECTIVE COATINGS ON BUILDING STRUCTURAL MEMBERS TO FRAME MITIGATION MEASURES TO PREVENT COATING SYSTEM FAILURES

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Abstract: A serious need has been raised to protect the building structural members from adverse effect of fire during a fire outbreak. Contemporarily fire protective coatings have been seen more prominently in use for their numerous advantages over conventional fire protecting barriers in passive fire protection systems. However, there have been frequent cases of defects, non-performance and eventually failure of coating prior to estimated design service life. Thus a need arises to efficiently plan for design intervention and execution stages of fire protective coating systems to enhance their performance and durability. This study aims to identify causes of defects and subsequent failures in coating system to frame mitigation measures in order to avoid the occurrence of failure by careful selection of fire protective coating based on its suitability with structural member and precautions taken prior to and during the application process of the coatings.

Index Terms - **Intumescent coating, vermiculite coating, Fire retardant coating, Fire resistant coating, Ablative coating, Passive Fire protection**

1. INTRODUCTION

Fire is a serious threat to people and lately it has been recognized as a threat to the building structures as well. The consequences of fire are tremendous economically and socially as well. Fire proofing has proved to be an effective measure in expanding the buffer time required for people to evacuate the building, while the structure remains stable.

Thermally induced forces can be a critical point governing the structural strength of building structural members, like steel, during fire and can induce deformations and stresses causing instability or progressive failure. (Lucherini & Maluk 2019)

(Porcari, Zalok & Mekky 2014) talks about high rise steel framed building structures which can be significantly affected by fire due to accidents and lead to further progressive collapse of the structure where progressive collapse of a building structure is referred to as an occurrence of a collapse of a structural segment when an initially localised failure element propagates to other elements of the building leading to massive structure failure. The most notable case of the same would be collapse of World Trade Center office building on September 11, 2001 due to large uncontrolled fire.

(Quintiere 2002) Suggested that the insulation thickness on the truss rods of the World trade center was insufficient which caused the over- heating of the steel as a result, this led to collapsing of trusses due to weakening.

(Porcari, Zalok & Mekky 2014) States that thermal barrier have been relied upon in the past for the protection of steel structure from fire and it has become extremely necessary to consider new innovative passive structural protection strategies so as to avoid progressive collapse. Building codes have addressed the need to protect structural elements by providing a covering material to steel structures in order to restrict the flow of heat to the member from exposure to elevated temperature for a specific period of time. This protection is typically prescribed in the form of fiber cememtitious coating or an intumescent coating. (Porcari, Zalok & Mekky 2014)

Passive fire protection system is a group of systems that compartmentalizes the building to avoid spread of fire through method of fire resistance. The system does not require any activation or manual participation of human. This is done through various methods by aiming at avoiding spread of flames or creating compartments which do not allow spread of fire due to difference in pressure between spaces.

One of the passive fire protection systems incorporates using coatings as thermal barriers to protect the substrates. The coatings act as barriers against heat and hence prevent high temperature from affecting structural performance of steel, concrete and wooden members. Traditionally, concrete covering, gypsum board and cementitious coatings have been used as passive fire proofing material which proved to be aesthetically unpleasing. To overcome this scenario, thin film coatings came into existences which are good in fire resistance as well as aesthetically pleasing. However, the market demands more function based performance and protective properties beyond the appearance.

Contemporarily, there has been a continuous demand for passive fire protection methods and usage of fire protective coatings to prevent adverse effect of fire on structure. This approach is being very effective in resisting building structure to collapse and thus new materials are being introduced in the market to serve the purpose.

Although these fire protective coatings can be significantly expensive as compared to other passive fire protection measures but they do reduce down the usage of space required and an appealing appearance of exposed surfaces unlike standard cementitious fire protection coatings, says (Rippe & Sam 2006). Thus, there is a growing demand in the market and people are becoming aware of these passive protection methods to be implemented in the building design. “These materials are becoming a more viable option. They can impart real fire protection,” (Rippe & Sam 2006) underscores.

1. 1 STRUCTURAL FIRE PROTECTION

When a structural member is exposed to fire, its behaviour is described as a concept of fire resistance in that situation. Fire resistance is the period of time a member performs to withstand under the effect of fire at which its limiting behaviour is seen. Structural fire protection ensures that the structural members of the building withstand its structural integrity during a fire condition. All structural members may not prove to give complete fire protection in terms of time and strength but have their own capabilities in respect to responding to heat. The members may even collapse after repetitive heating due to loss in ability to support a load.

The main objectives of the structural fire protection in a building can be considered as to maintaining the integrity of the building by restricting the size of the fire and preventing the structure from becoming unstable when exposed to fire.

1.1.1 PERFORMANCE OF STEEL EXPOSED TO FIRE

Quick fabrication, rapid designing and speedy erection makes steel framed structures to be an important structural element which is extensively used in construction industry. Although steel is not susceptible to combustion during fire, it does have a limitation of losing load bearing strength and integrity to almost half from the original at achieving temperature of approximately 500˚C. This might also lead to very serious consequences such as progressive collapsing of structure due to loss in mechanical properties.

Therefore, it becomes indispensible to protect exposed steel in such structures from fire to prevent fire induced losses to structure by providing passive fire protective system. This indeed ensures that sufficient time is available for both evacuations of building and fire men to move in. (Puri & Khanna 2016)

1.1.2 PERFORMANCE OF STEEL EXPOSED TO FIRE

Duration of exposure and temperature are both crucial factors determining the degradation of wood during fire exposure. Although, wood is a good combustible material, its fire performance depends on its physical properties like its cross sectional area, its chemical composition and whether the wood is hard or soft. It degrades when exposed to elevated temperatures in form of char, where charring rate depends upon its moisture content. Failure is the moment when charring equals the thickness of the wooden member.

1.1.3 PERFORMANCE OF STEEL EXPOSED TO FIRE

Concrete has been taken for granted in view of its thermal performance considering the fact that it has an ability to protect self as a thermal barrier and also by not spreading the flames further. However, recent experiments have concluded that concrete gets adversely affected by extreme temperature exposures. It has free water molecules present within its structure that are imparted from cement. Continuous transference of heat into the structure causes significant rise in temperature in form of heat flow leading to evaporation of water molecules. This dehydration of concrete leads to formation of cracks which are vulnerable regions for reinforcement bars to get exposed to fire and hence, provide a pathway for direct heating of reinforcement bars.

Another issue observed when concrete is exposed to fire is spalling which is the phenomenon of explosive ejection of concrete chunks from the surface of the material, due to the loss in surface tensile strength. Irregular heating and cooling of concrete surface induces thermal stresses within the structure. The spontaneous heating leads to rapid expansion of moisture within concrete leading to rise in water pressure.

1.2 TYPES OF FIRE PROTECTIVE COATINGS

Fire retardant coatings are applied to combustible materials (wood, plastic, foam) and are designed to reduce the rate of flame spread. These coatings can be categorised into two groups: non-intumescent and intumescent coatings. Non-intumescent coatings are fundamentally decorative, architectural coatings that contain fire retardant additives intended to diminish the pace of fire spread and smoke improvement of burnable substrates. (Mariappan 2017)

Intumescent coatings are thin film coatings with dry film thickness of not more than a few millimeters which are thermally reactive in nature. These coatings are a combination of an acid source, a carbonaceous compound and a blowing agent. Upon heating, the layer swells up to form low density and thermal low conductivity char acting as a thermal barrier says (Lucherini & Maluk 2019). These are mainly applied for cellulosic fire conditions.

Ablative coatings are designed to self-burn at very slow pace during a fire outbreak and protect the substrate beneath. As the burning of ablative coating is on a gradual pace, it is responsible to provide ample time for suppression of fire by external means. This is the fundamental by which ablative coating protects the structural member. (Mróz, Hager & Korniejenko 2016)

Fire resistant coatings are comparatively thicker than fire retardant coatings when applied over the substrate and are usually applied over non-combustible materials to avoid damage to substrate or any spread further. Intumescent coatings and Vermiculite coatings are predominantly applied over steel structures and concrete.

Vermiculite plaster coating is a thick protective coating applied over the structural member. The coating being composed of vermiculite along with gypsum or cement makes it a good heat resistant barrier. It is very efficient at retaining moisture, thus during a fire outbreak the material turns to steam creating a cooling effect on the structural member and thus delays rise in temperature. The density being low makes the heat transfer through the coating very slow and thus no substantial amount of heat gets transferred to the substrate below due to low thermal capacity. (Xue, Zhang & Yang 2014)

1.3 Aim

To analyse suitability of fire protective coatings on building structural members and frame mitigation measures for coating system failures to enhance performance and durability of fire protective coatings.

1.4 Objectives

1) To develop an understanding of types of coatings applied on structural members and scientific principles for enhancing fire performance.
2) To establish parameters of suitability of fire protective coatings and analyse the same for various structural members
3) To identify causes leading to non-performance and poor durability of coating
4) To develop mitigation measures for coating system failures to enhance performance and durability of fire protective coatings

1.5 Methodology

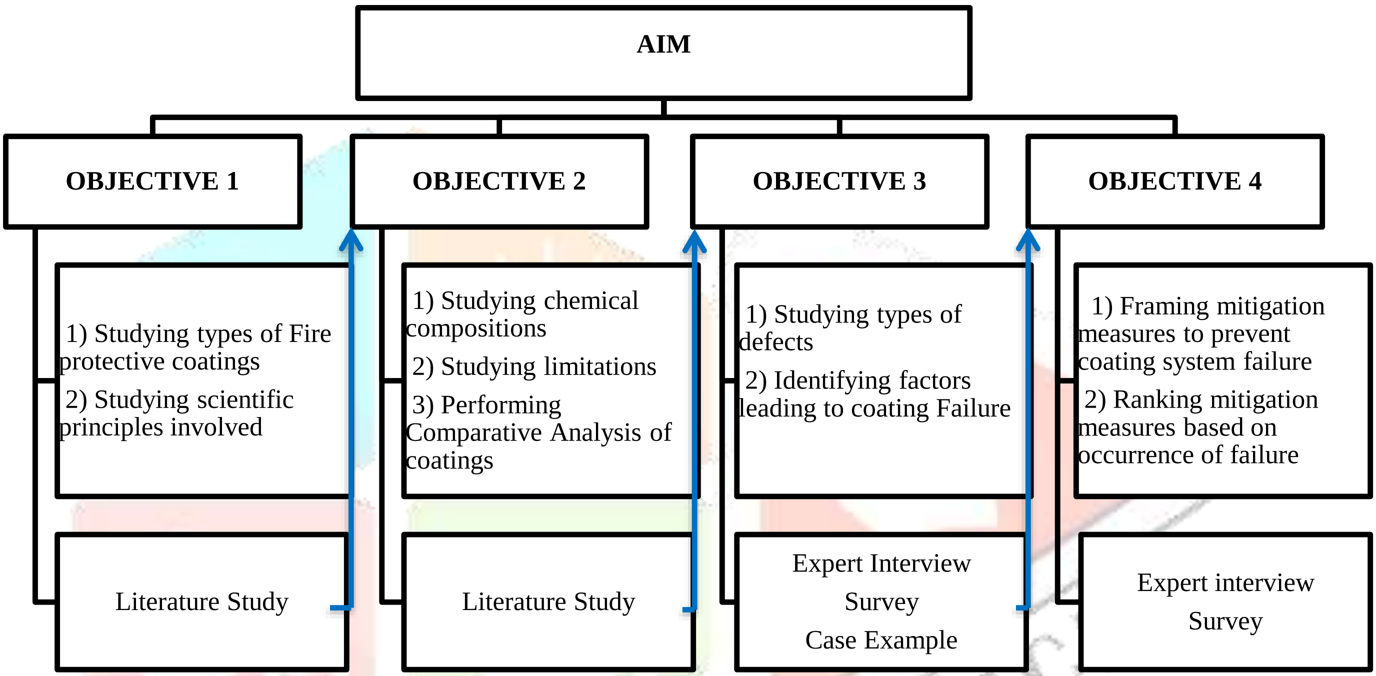

Figure 1 Flowchart of Methodology

2. Factors leading to defects and poor durability of coating system

The achievable design life period of coating is the time period in which it successfully performs to fulfill the ability to protect structural member from harmful effect of fire. The non-performance of a fire protective coating in terms of protecting the structural member from exposure to fire conditions is referred to as failure.

Few of defects can be visually detected due to deformed appearance of coatings while few need a detailed analysis. All defects may or may not lead to a coating system failure however; their root cause of occurrence has to be examined based on several factors considering the history of application. The reason may be one or consequences of many factors which would ultimately lead to a failure.

Table 1 Factors leading to Defects in Fire protective Coating System

Application specific
• Tools and applicators not in good working condition
• Inappropriate Dry Film Thickness / Wet Film Thickness
• Improper drying, curing and over coating times
• Incorrect formulation of product
• Surface contamination due to improper cleansing of surface before application
• Loss of adhesion between coating system
• Inconsistency in thickness during application may cause sagging (Improper dilution and mixing of coatings) • Too much dilution leads to highly viscous coating which runs off the surface leaving the region uncoated • Too thick coating leads to formation of lumps
• Application of coating at too low temperature
• Heavily pigmented coating solution due to improper mixing
Coating system

• Incompatibility of coating system
• Product has exceeded shelf life
Labour specific issues
• Unskilled labour
• Communication gap between site supervisor, contractor and labour
Contractor specific
• Lack of understanding of drawings
• Lack of regular supervision
Other Factors
• Adulteration in consignment - to increase volume of package
• Communication gap between client and supplier (In case of application of fire protective coating in existing building structure)
• Alterations in design after the application of fire protective coatings causing penetrations in coatings
• Environmental exposure
• Impact damage due to external factor

The image (Fig. 2) shows formation of bubbles in thin film intumescent coatings. As the bubbles burst open due to environmental exposure, the region under the bubbles becomes exposed to moisture, due to which the topcoat of the paint may fall off. This may cause the inner coating to corrode thus making structural member vulnerable to failure during fire.

Figure 2 Bubbles formation in thin film Intumescent coating

Figure 3 Sagging of paint due to inappropriate mixing of coatings

The slight sagging seen on the painted surface (Fig. 3) becomes a point of failure when the surface comes under exposure to fire. As the Dry Film Thickness is much higher than the regions surrounding it, the sagged region becomes heavier when charred making it unstable and unsuitable to support the self-weight. Thus, the charred material falls off making the structural member exposed to fire.

The region of crack (Fig.4) development becomes vulnerable to moisture through air causing corrosion in the member. As the cracks open up a passage to the inner surface, the coating tends to deteriorate causing failure of structural strength of member at the time of fire.

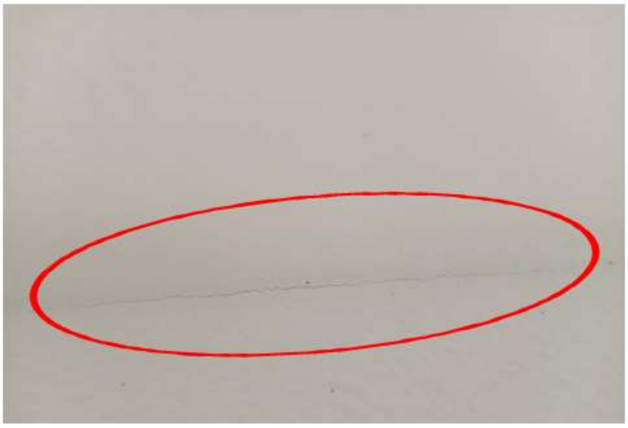

Figure 4 Crack formation in intumescent coating

Figure 5 Top coat peeling off

The picture (Fig. 5) clearly depicts the fire protective coating, peeling off from the structural column. The possible reasons being - application of multiple layers of coating over previous coating, damage from rainwater, damage due to UV rays exposure on coating, lack of adhesion due to inappropriate selection of epoxy resin.

3. TYPES OF DEFECTS IN FIRE PROTECTIVE COATINGS

Table 2 Types of defects in fire protective coating system with their possible causes

Cause		Peeling off	Blisters	Sagging	Formation of Cracks	Delamination	Abrasion	Alligatoring	Crazing	Cratering	Settlement	Stress Cracking
Application Process	Lack of adhesion	✓	✓			✓						
	Application of multiple layers of coat	✓				✓						
	Exceeding the over coating time.	✓										
	Inappropriate tool used for application		✓	✓								
	Surface contamination	✓			✓	✓						
	Insufficient recoat intervals				✓	✓				✓		
	Highly viscous paint solution			✓								
	Inappropriate WFT	✓	✓	✓		✓		✓		✓		
	Application at too low temperature		✓		✓			✓	✓			✓
Coating System	Incompatibility between coating systems	✓							✓			
	Incorrect formulation of product			✓							✓	
	Old stock										✓	
	Heavily pigmented paint	✓		✓					✓	✓	✓	
Substrate	Expansion/Contraction of substrate				✓	✓	✓	✓				✓
	Impact Damage					✓						
	Weathering exposure	✓					✓					

The causes of failures can be broadly identified in three scenarios: Substrate related failures, coating system related failures and application process related failures. Among the three factors, application process has the highest occurrence level of defects followed by coating system related defects. These are the vulnerable factors that govern that frequency of failure occurrence. Thus, precautions are to be taken during the design stage and execution stage of these coating systems to minimize to occurrence of coating failure.

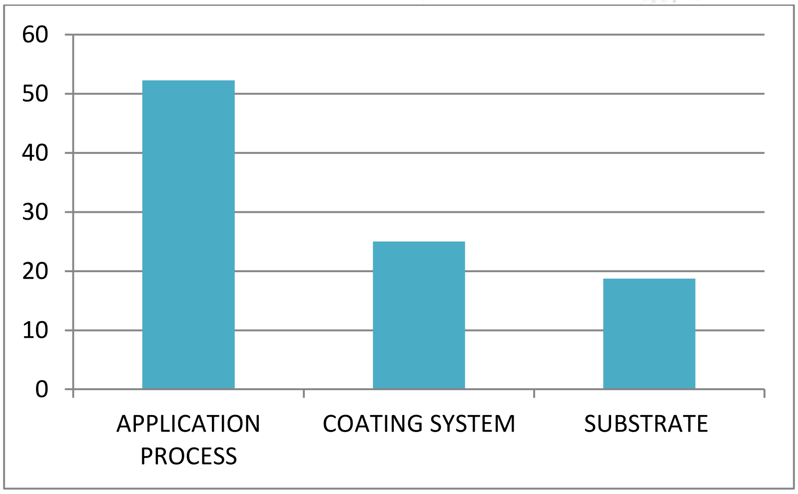

Figure 6 Frequency of defects

Application process related failure	52.25 %
Coating system related failure	25 %
Substrate related failure	18.75%

4. MITIGATION MEASURES FOR FIRE PROTECTIVE COATING SYSTEM FAILURES

The following figure showcases stage wise division of implementation process of fire protective coating system from initialisation at pre application stage, commencing with selection of coating system and installation at execution stage to precautions taken at both pre and post application stages and lastly maintenance post application.

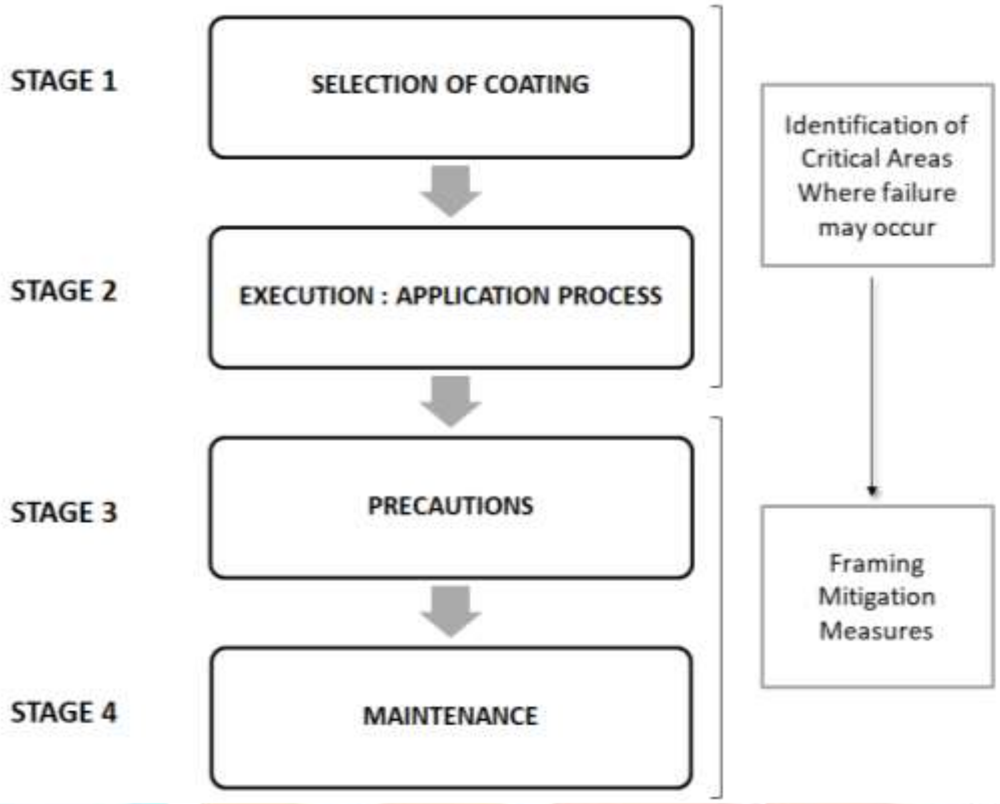

Figure 7 Flowchart of intervention stages

4.1 SELECTION PROCESS OF FIRE PROTECTIVE COATING

The selection criteria of fire protective coatings systems, comprising the base coat, fire protective coating and the top coat is very specific to the proposed area where the coating is to be applied. However, the initial choice of protective coating is based on the client's requirements, whereas the selection of base coat and the top coat are subjected to compatibility with the protective coating. The selection of coating begins with the type of fire load to be catered to with respect to cellulosic fire and hydro carbonic fire. Further, the selection criteria depends on the type of structural member to be protected; say wood, steel or concrete followed by the desired fire resistant time for the member as thickness of coating is directly proportional to the fire resistant time. However, thickness of coating is also dependent on the section size of the member being coated with protective coating, failure temperature of member, fire load in specified region and heated perimeter of structural member.

Protective coatings are preferentially used over conventional passive fire protection systems for the purpose of fulfilling demands of aesthetics. Thin film coatings prove to give smooth finish as compared to thick film coatings. Therefore, members that are directly exposed in a region shall be covered with thin film protective coatings whereas the unexposed members can be protected with thick film coatings which are not as appealing as thin film coatings yet can be efficient in cost cutting due to the fact that thin film coatings are comparatively expensive than thick film coatings for their added on advantage of aesthetics.

The next step is to see whether the member is exposed to outdoor environment or remains unexposed as coatings are very specific in regard to exposure conditions and thus, not all coatings can be used externally. For example, gypsum being vulnerable to moisture makes it impossible for gypsum vermiculite coating to be applied externally. Accordingly, the selection shall be done so as to reduce chances of vulnerability to unfavorable factors which would eventually reduce down the durability of coating. Lastly, the selection is based on finished appearance of the coatings. Fire retardant varnishes can be preferred when natural appearance of the member is to be retained, such as in case of wood. Fire retardant paints, ablative paints and intumescent paints can be used in various colors for clean finish and desired appearance of member. Vermiculite coatings are not usually preferred to fulfill the demand of aesthetics, thus they are applied of unexposed surfaces.

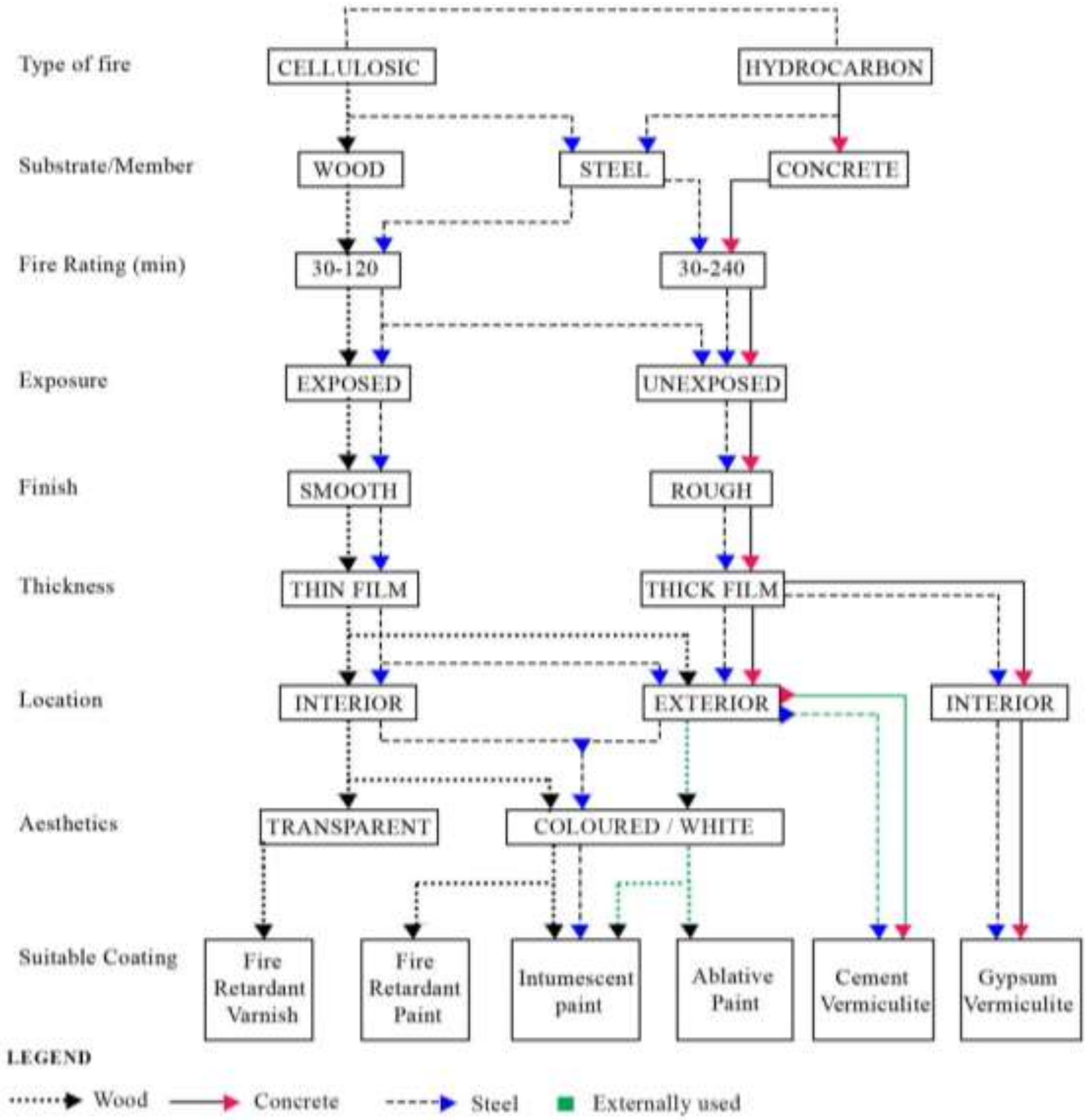

Figure 8 Flowchart for Selection process of fire protective coating

4.2 Mitigation Measures

The mitigation measures have been framed in consideration to the 'risk factors' – Coating system, Application process and Substrate, which reflect high frequency of defects that gradually lead to a coating system failur

Table 3 Mitigation measures to prevent Coating system failure

	Risk Factor – Coating System	RII	Rank
A1	Compatibility of coating system must be checked prior to commencement of application.	0.87	1
A2	Product shelf life must be checked prior to application and shall not exceed the date mentioned on the product.	0.71	3
A3	Mixing should be in accordance with the manufacturer's instructions.	0.84	2
A4	All material containers shall remain closed until needed to be applied.	0.41	6
A5	Adequate time interval shall be maintained while recoating over previous coat.	0.63	4
A6	If any error is observed in the application process, all coatings shall be removed and reinstalled.	0.55	5
	Risk factor - Application procedure	**RII**	**Rank**
	Coating related measures		
B1	The surface must be cleaned prior to application process by sand blasting, suitable emulsifying degreasers, or steam cleaning in case of oil and grease or as specified in the project.	0.89	1
B2	Coating thickness must be decided on the basis of desired fire rating, section size of structural member and fire load.	0.82	3
B3	Wet film thickness of thin film coatings and density of thick film coatings must be checked simultaneously while the application process is being carried out parallel.	0.83	2
B4	Dry film thickness must be checked when the coating is completely dried.	0.27	6

B5	Adhesion test (Pull over test, Cross cut test) must be conducted only when coating is completely dried.	0.57	5
B6	As Cross-Cut Adhesion test is a destructive test it should be carried out as per site requirements instructed by contractor.	0.63	4
	Other measures	**RII**	**Rank**
C1	Exposure conditions like temperature, relative humidity and dew point on site must be checked prior to commencement of application process.	0.78	4
C2	If the site is too humid, windy the mixing of coating and solvents shall be done just prior to application only.	0.69	7
C3	All tools and equipment must be checked once brought on site.	0.75	5
C4	The applicator shall be selected depending upon the complexity of region to be painted and site condition.	0.8	3
C5	Ensure Tools and applicators fulfil the technical requirements given by the manufacturer.	0.61	9
C6	To check availability of coating material from the supplier/manufacturer to meet the requirements.	0.65	8
C7	All drawings shall be read thoroughly on site before commencing application process.	0.82	1
C8	Skilled labour must be appointed for the application work.	0.7	6
C9	On site supervisor shall make sure that labour is following the instruction.	0.81	2
	Risk factor – Substrate	**RII**	**Rank**
D1	If any member undergoes repair work which may lead to puncturing of member, it shall be recoated with protective coating following same application procedures.	0.82	2
D2	In case of damage caused by internal stress in member or external impact on substrate, the coating system must be reinstalled.	0.9	1

5. Results and Discussions

Following graphs depict the ranks of mitigation measures based on importance factor categorized into risk factors catering to frequency of defects leading to coating system failure. Relative importance index method has been used for ranking the mitigation measures as per the categories: Application Process, Coating system and Substrate.

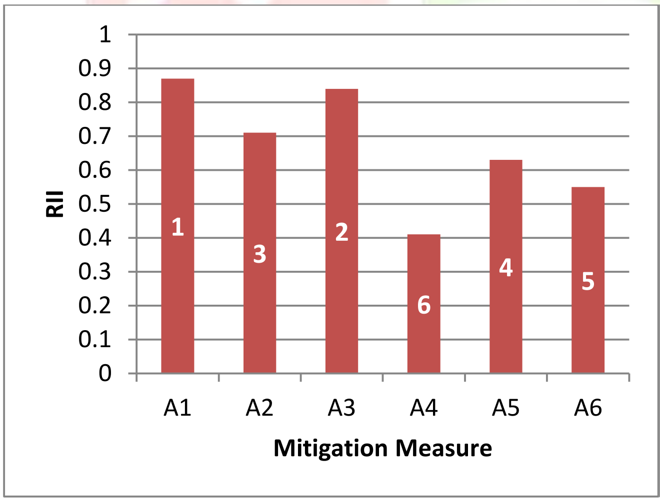

Figure 9 Ranking of mitigation measures related to Coating system

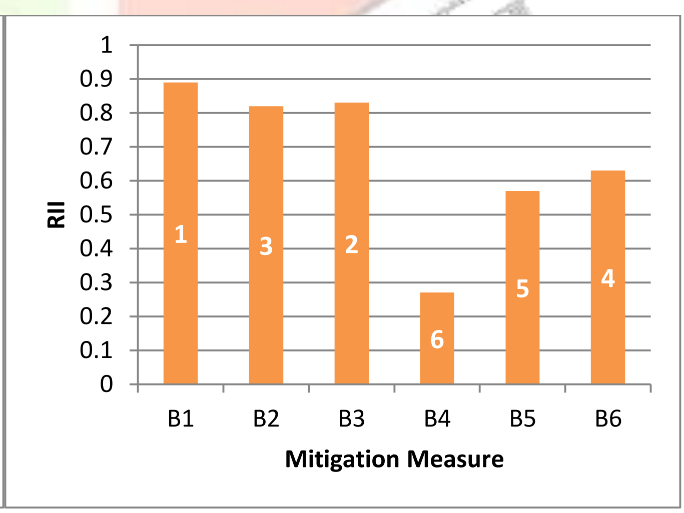

Figure 10 Ranking of mitigation measures related to coatings during application

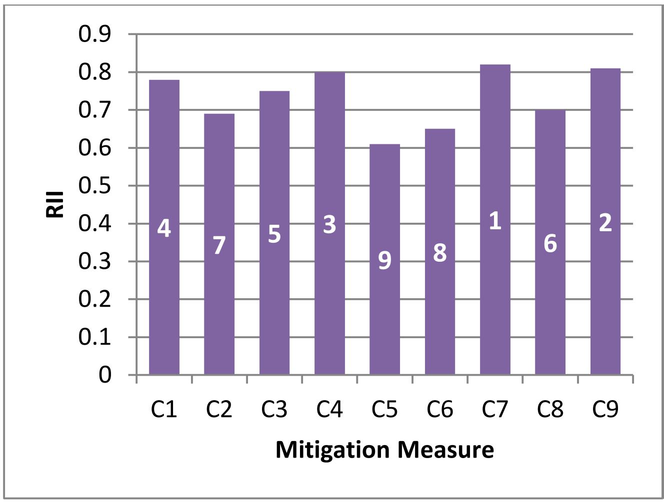

Figure 11 Ranking of mitigation measures related to External factors during application process

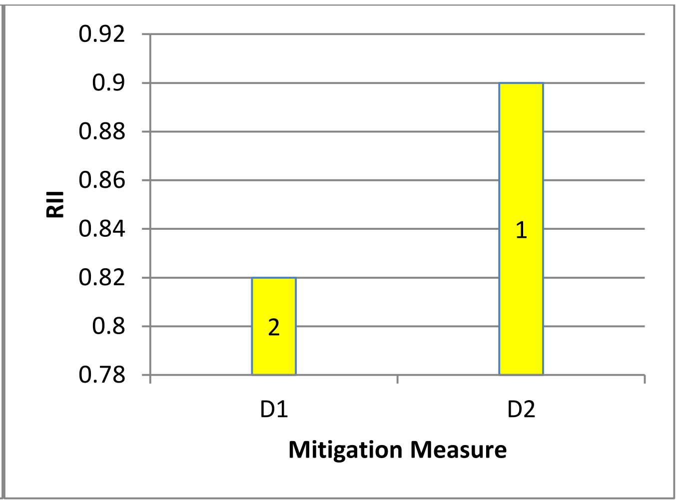

Figure 12 Ranking of mitigation measures related to substrate

6. CONCLUSION

1) Fire protection of building structural members is highly important to safeguard the lives and the loss to the structure during a fire outbreak. Reaction to fire is a material characteristic. In order to reduce the probability of on outbreak and consequent growth of fire, the structural elements need to be not easily ignitable by fire and ensure that the structural member does not spread fire further more. Therefore, the structural members can be treated to reduce their ease of ignition from a small source and thus, the treatments may not affect their rate of burning once ignited.

2) The coating system performs well without failing under conditions subjected to right selection of coating with respect to the structural member proposed to be protected. The selection of coatings system is also a very critical decision and vulnerable area for an occurrence of failure which is based on the compatibility of coatings and attributes related to it. However, the most commonly seen defect happens to be incurred during the application process of the coatings on site.

3) The performance of fire protective coatings is in depth dependent on the selection of suitable coating system and the steps involved in application process involving labour component. The success rate of coating system is highly related to following the right precautionary steps during execution on site and further maintaining the top coat at regular intervals which would protect the underlying fire protective coating during the long run.

4) Design intervention stage and execution stage for fire protective coatings are crucial stages with high possibilities of occurrence of defects, hence, enhancing the vulnerability of failure of coating system. Therefore, attention must be paid at the design intervention stage and execution stage.

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