



Visual Indicator-Based Thermal Inference (VITI) for Post-Fire Structural Assessment

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ABSTRACT

This research introduces Visual Indicator-Based Thermal Inference (VITI) methodology, a practical and cost-effective approach for preliminary visual assessment of fire-damaged structures. Existing post-incident assessment methods often face limitations, particularly in developing countries where advanced testing equipment may be limited or unavailable, and frequently fail to translate observed damage into quantitative temperature exposure data. The VITI methodology fills this gap by using systematic visual observation and material degradation analysis to infer the temperature exposure and structural implications. It comprises three key steps: structured evidence captures (photos/videos, indicator extraction), mapping these indicators to temperature bands based on material behaviour at elevated temperatures, synthesizing this information to bound zone-level temperatures and evaluate potential structural implications. The methodology applicability and reliability are shown through two case studies: an industrial Reinforced Concrete (RC) structure subjected to a dust explosion followed by fire, and a residential load-bearing masonry structure with RC elements damaged by fire. The VITI offers engineers and assessment teams a valuable tool for immediate, reliable, and cost-effective initial structural evaluation, especially for RC and load-bearing masonry structures which are dominant in developing regions. However, the method has inherent limitations including uncertainty in temperature estimation due to exposure duration, material variability, and ventilation effects, and it should be regarded as a preliminary screening tool that may require supplementary non-destructive or destructive testing for critical structural decisions.

1. INTRODUCTION

The assessment of structures subjected to fire incidents represents a critical challenge in structural engineering, particularly in developing countries where advanced testing equipment may be limited or unavailable. Existing assessment methods often rely on sophisticated laboratory testing and expensive non-destructive testing equipment, making comprehensive structural evaluation challenging in many contexts. Also, existing post-fire assessments frequently list observed damage but do not convert those observations into quantitative temperature bounds linked to specific damage mechanisms such as cracking, spalling, and bond degradation at known temperature thresholds. This research addresses this gap by presenting a practical Visual Indicator-Based Thermal Inference (VITI) method-

ology for post-fire structural assessment that primarily relies on visual observation and material degradation analysis to infer temperature exposure and evaluate potential structural implications.

The significance of this research lies in its practical applicability to real-world scenarios where immediate structural assessment is required following fire incidents. By establishing correlations between observable material degradation patterns and temperature exposure ranges, this methodology provides engineers and assessment teams with a valuable tool for initial structural evaluation. The approach is particularly relevant for Reinforced Concrete (RC) and load-bearing masonry structures, which represent the predominant construction type in many developing regions.

The research contributes to the existing body of knowledge by providing a validated framework for

temperature inference through material degradation analysis, offering a cost-effective assessment method while maintaining reliability and accuracy in structural evaluation.

2. LITERATURE REVIEW & THEORETICAL BACKGROUND

One of the most common and catastrophic events in the world is the disaster caused by fires.

RC structures exhibit complex behaviour when subjected to elevated temperatures from fire. The material properties of concrete undergo significant changes as temperature increases, with these changes serving as indicators of thermal exposure experienced by structure [2], [3], [4], [5], [6], [7], [8].

The effects of fire on reinforced concrete elements are complex and multi-faceted. Concrete spalling, which involves the detachment of surface layers, is one of the most significant forms of fire damage. Explosive spalling typically occurs between 250-420 °C due to pore pressure build-up, while progressive spalling may develop at higher temperatures (above 300 °C) as moisture migrates through the concrete matrix [7], [11] (Table A.1). Cracking patterns vary from minor surface crazing at temperatures below 300 °C to deep structural cracks above 500 °C.

With respect to mechanical properties, concrete may retain most of its compressive strength up to approximately 300 °C, but experiences a reduction of 10-50% at 300-500 °C and 50-80% at 500-700 °C, depending on aggregate type, porosity, heating rate, and exposure conditions [8], [10], [11]. At temperatures exceeding 800 °C, concrete undergoes severe degradation, and residual strength may reduce to very low levels. The elastic modulus degrades more rapidly than compressive strength, typically losing 20-30% by 300 °C and continuing to decrease at higher temperatures.

For reinforcement steel, the yield strength is generally retained up to approximately 500-600 °C, with significant reduction occurring at 600-700 °C. Exposure beyond 700-800 °C may lead to substantial loss of strength and potential buckling, particularly where spalling has exposed reinforcement directly to fire. Bond strength between concrete and steel also degrades progressively with increasing temperature [3], [12], [14].

Extensive research has shown that fire temperatures exceeding 900 °C affect most common building materials [9], while non-metallic materials such as plastics and paints exhibit blistering or melting at much lower temperatures, providing useful supplementary indicators of thermal exposure (Table A.4) [13].

According to established research, concrete colour changes which result from chemical and physical transformations within the concrete matrix, provide useful indicators of temperature exposure. However, it should be noted that concrete colour change depends heavily

on the aggregate type; for example, siliceous aggregates (e.g., river gravels) show more pronounced colour changes, while calcareous or lightweight aggregates may exhibit less distinct transitions. Therefore, colour change alone should not be considered a universally reliable indicator and must be interpreted in conjunction with other observable evidence [12], [18]. These chemical changes are accompanied by thermal expansion, which can lead to cracking and spalling of concrete surface [12], [14], [1], [7].

Table A. 3 summarises the established relationship between concrete colour changes and temperature exposure: concrete generally retains its original colour below 300 °C; turns pink or red between 300-600 °C (with 0-55% strength reduction); becomes whitish grey at 600-900 °C (55-85% reduction); buff at 900-1000 °C (85-100% reduction); and yellow above 1000 °C (complete decomposition). These colour transitions are more pronounced in siliceous aggregates and less reliable for calcareous or lightweight aggregates [12], [18].

Table A. 4 presents a comprehensive reference of temperature indicators for common construction materials. Key thresholds include: paint deterioration at ~100-150 °C; common plastics (polystyrene, polyethylene, PVC) softening and melting between 120-200 °C; wood ignition at ~240 °C; solder lead melting at ~250-400 °C; zinc melting at ~420 °C; aluminium melting at ~600 °C; glass softening at 500-600 °C; silver melting at ~900 °C; and copper melting at 1000-1100 °C. Brick deterioration ranges from 200-600 °C (solid clay) to 300-900 °C (hollow clay) [12], [3], [15], [16], [17]. These thresholds serve as the basis for non-structural material indicator mapping in the VITI methodology.

When evaluating structural integrity following fire exposure, a systematic approach is adopted and divided into level 1 and level 2 assessment. Level 1 which is known as Preliminary Investigation begins with ensuring safe entry, followed by a general inspection to assess visible damage. This step forms the basis for further testing and sampling. While level 2 integrates material testing, fire severity analysis and pressure damage map to evaluate material performance degradation. Despite advancements, challenges remain in employing numerical methods due to the high costs of laboratory studies [12], [11], [13].

Current assessment methods for fire damaged concrete structures can be categorised into three main groups: Destructive Tests (DT) on core specimens, Semi-Destructive in-situ tests, and Non-Destructive Testing (NDT) methods. Each category offers different advantages and limitations in terms of accuracy, cost, and practical applicability [11].

For RC structures NDT such as Ultrasonic Pulse Velocity (UPV) and Rebound Hammer test (RHT), are used to assess concrete integrity. While DT like adapted core sampling, Semi-destructive Tests like pull-off test

and subsequent laboratory test on these samples like X-Ray diffraction test are used to provide deeper insights into strength loss and temperature distribution in cross section. However, these methods may have limitations in heavily damaged structures and require skilled interpretation of results [12], [3], [20], [21], [18], [11], [22].

Visual assessment represents the most accessible and cost-effective method for initial structural evaluation following fire incidents. This approach relies on systematic observation of material degradation patterns, colour changes, and structural deformation to infer the conditions experienced by the structure [23], [24].

Colorimetric analysis, which involves inferring temperature exposure through concrete colour changes, provides a simple yet effective assessment tool [21]. This method is particularly valuable in situations where immediate assessment is required and advanced testing equipment is not available. The reliability of colorimetric analysis depends on understanding the relationship between temperature exposure and observable colour changes, as well as recognising the influence of aggregate type and cement composition on concrete colour development. This method enables a detailed analysis of the colour but is time-consuming [12], [3], [21], [11], [22].

An additional complementary assessment technique is the phenolphthalein indicator test, which is used to determine the depth of carbonation in concrete. When a phenolphthalein solution is sprayed onto a freshly exposed concrete surface, areas with a pH above approximately 9.2 (uncarbonated concrete) turn pink, while carbonated zones remain colourless. In fire-damaged concrete, the depth at which the concrete has been chemically altered by heat can sometimes be estimated using this method, as elevated temperatures accelerate carbonation and decomposition of calcium hydroxide. This quick and inexpensive technique can supplement visual assessment by providing an indication of the depth of fire-affected concrete, particularly when combined with other indicators [3], [12], [22].

The effectiveness of visual assessment can be enhanced through systematic documentation using photography and detailed observation records. This approach allows for comprehensive evaluation of damage patterns and provides a basis for more detailed assessment if required.

In practice, post-fire structural assessment is most effective when conducted within a hierarchical framework: Rapid visual screening (Level 1), followed by targeted Non-Destructive Testing (Level 2), and selective destructive testing (Level 3) where warranted. NDT methods such as Ultrasonic Pulse Velocity (UPV), Rebound Hammer Test (RHT), infrared thermography, and pull-off tests are commonly employed to evaluate internal damage and residual strength [12], [20], [22]. The VITI methodology proposed in this re-

search is positioned as a first-level rapid screening tool that guides the targeted application of NDT methods, particularly for critical structural members. By systematically bounding the temperature exposure through visual indicators, VITI enables engineers to prioritise which zones and members require more detailed Level 2 or Level 3 investigation, thereby optimising the use of limited testing resources.

3. METHODOLOGY

This research employs a systematic evaluation framework based on visual observation and material degradation analysis to infer temperature exposure and offer preliminary visual assessment. The methodology emphasises the relationship between observable material changes and temperature exposure ranges, applying established guidelines for concrete colour changes and patterns of degradation. This analysis is supplemented by observation of other degradation indicators, including surface spalling, cracking patterns, and changes in material texture. This correlation forms the basis for temperature inference and subsequent structural evaluation.

The VITI methodology explicitly addresses the following observable fire damage mechanisms in concrete structural members: (a) Spalling - differentiated into early-stage explosive spalling (typically 250-420 °C, driven by pore pressure) and late-stage progressive spalling at sustained elevated temperatures; (b) Cracking patterns - ranging from minor surface crazing (below 300 °C) to deep structural cracking (above 500 °C); (c) Reinforcement steel deformation or buckling which is a significant fire damage indicator suggesting direct high-temperature exposure of reinforcement, often following spalling of the concrete cover; and (d) Depth of concrete deterioration which assessed through visible cross-section damage, spalling depth, and colour changes through the member thickness. These mechanisms are evaluated alongside non-structural material indicators to establish a comprehensive temperature profile for each assessed zone.

The methodology incorporates validation through comparison with other observable indicators, such as the behaviour of non-structural materials, metal components, and other construction materials. This multi-indicator approach enhances reliability of temperature estimates and provides confidence in assessment results. It should be noted, however, that observable temperature indicators on non-structural elements (e.g., melted plastics, paint damage) do not necessarily reflect the actual temperature experienced by the structural concrete core, which is often significantly lower due to the thermal insulation properties of concrete cover and the heat sink effect of the structural mass. The VITI methodology accounts for this by cross-referencing non-struc-

tural indicators with direct concrete indicators (colour, spalling, cracking) and applying conservative interpretation when bounding structural temperatures. This methodology, termed Visual Indicator-Based-Thermal Inference (VITI), represents a novel contribution by integrating a structured three-step framework that systematically links field-observable indicators to quantitative temperature bands through multi-indicator synthesis and explicit temperature-bounding logic. While visual assessment methods exist in current practice, the VITI approach is distinctive in its systematic codification of indicator-temperature relationships, its emphasis on cross-referencing multiple independent indicators within spatial zones, and its provision of a reproducible decision framework for field engineers.

VITI proceeds in three steps:

1. **Evidence captures:** Structured visual survey (photos/videos), location-based logs, and extraction of indicator instances (e.g., paint blistering, melted plastic covers, soot deposition, localised RC spalling, mortar discolouration). Where feasible, the phenolphthalein indicator test may be applied at this stage to assess the depth of fire-affected concrete by spraying the indicator solution onto freshly exposed surfaces.
2. **Indicator-temperature mapping:** Map each indicator to a temperature band using tables on material behaviour at elevated temperature; prioritise indicators occurring in the same compartment/zone.
3. **Synthesis:** Bound zone level temperature by intersecting the indicator-derived ranges, then translate the thermal envelope into structural implications (e.g., likely negligible RC strength loss $\leq \sim 350$ °C; potential finish damage).

Based on the temperature bounds derived from the synthesis step, the assessed zones are classified into the following damage categories: Category I (Negligible Damage, estimated temperature below 300 °C): cosmetic damage only, no significant loss of structural capacity; finishes may require repair. Category II (Minor to Moderate Damage, 300-500 °C): possible surface strength reduction in concrete, some spalling; structural capacity likely adequate but detailed assessment recommended for critical members. Category III (Significant Damage, 500-700 °C): substantial concrete strength loss, reinforcement properties potentially affected; comprehensive NDT and possible core testing required. Category IV (Severe Damage, above 700 °C): major structural degradation, reinforcement buckling or fracture likely; member replacement may be necessary.

Not all visual indicators carry equal diagnostic reliability. Accordingly, the VITI methodology groups indicators into three confidence tiers that drive the decision logic. Tier 1 (high-confidence structural indicators) includes concrete colour changes (for siliceous ag-

gregates), the presence or absence of spalling and cracking, and the exposure of or damage to reinforcement, which are directly related to thermal and mechanical distress of the RC member. Tier 2 (threshold-based indicators) comprises melting, softening or distortion of metals, glass, plastics and other non-structural elements with well-established temperature thresholds. Tier 3 (supporting indicators with lower confidence) includes soot deposition patterns, paint damage extent, and mortar discolouration, which may be influenced by ventilation conditions, fuel type, and exposure duration.

When indicators from different tiers suggest conflicting or overlapping temperature ranges, the VITI methodology adopts a conservative approach: the upper bound of the temperature envelope is governed by the highest-confidence available indicator (Tier 1 > Tier 2 > Tier 3), and a precautionary margin is applied when ambiguity persists. Where key Tier-1 indicators are absent or unclear and only Tier-2/3 evidence is available, the resulting estimates are treated as low-confidence and the engineer is advised to recommend supplementary NDT investigation rather than relying solely on the visual evidence. Sources of uncertainty in temperature inference include variations in fire exposure duration, moisture content, and the potential masking of indicators by soot deposits or subsequent weathering. The flow chart in **Figure 1** summarises the VITI decision logic.

The two case studies presented in this research were selected to demonstrate the practical application of the assessment methodology across different structural types and incident scenarios. Factory X represents an industrial RC structure subjected to dust explosion and fire, whilst the residential case study involves a load-bearing masonry structure with RC elements subjected to fire damage.

The analysis approach for each case study follows the established assessment framework, beginning with systematic documentation of observed conditions and progressing through material degradation analysis to temperature inference and structural evaluation. The methodology is adapted to the specific characteristics of each case whilst maintaining consistency in the overall approach.

Data collection for Factory X utilised professional assessment reports from the University of Khartoum Consultancy Corporation (UKCC), providing detailed documentation of structural conditions and test results. The residential case study relied primarily on photographic evidence provided by the property owner, demonstrating the applicability of the methodology in situations where detailed professional assessment may not be immediately available.

Factory X is a wheat flour-processing facility located in Sudan. The facility experienced a significant dust explosion combined with fire in 2022 [25], under

one of the flour bins in section B, leading to a complete halt in operations. The facility, an RC multi-story framed structure, comprises Wheat Silos, Production Hall, Flour Bins, Packing Platform, along with steel shed (Warehouse), as shown in **Figure 2**.

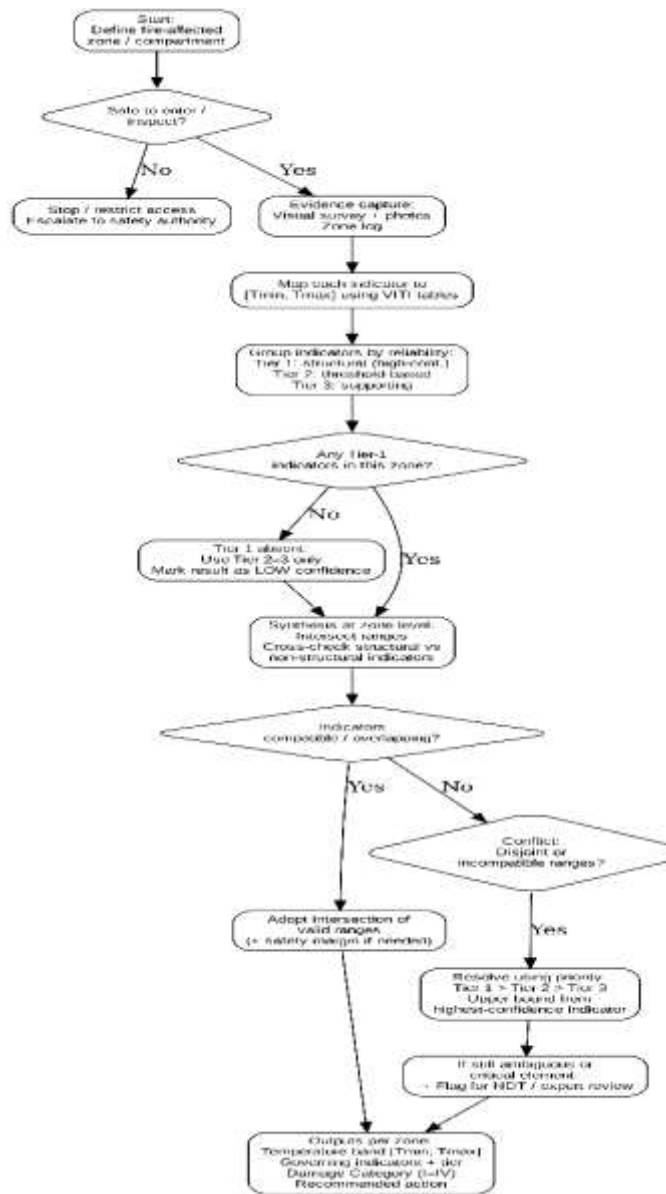


Figure 1: VITI decision flowchart; indicator reliability tiers and handling of conflicting evidence

4. RESULTS

4.1 Case Study 1: Factory X (Industrial RC Structure)

According to National Fire Protection Association (NFPA), dust is any finely divided solid below 420 μm , that when dispersed in air, poses a fire or explosion risk, with over 70% of industrial dusts being combustible [26], [27]. A dust explosion is initiated by rapid burning of combustible particulates suspended in air. Any solid material that can burn in air will do so with a violence

and speed that increases depending on particle size. But dust explosions require “Dust Pentagon” factors [28].

The fire temperature during the incident at Factory X was most likely in the range of 300-350 $^{\circ}\text{C}$, high enough to damage plaster, paint, plastics and non-structural elements, but not sufficient to cause major loss of

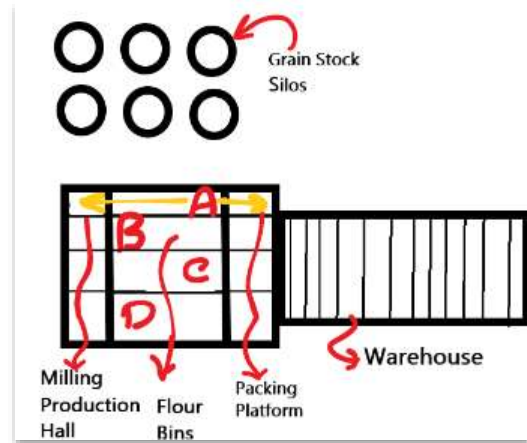


Figure 2: Factory X, Flour Mills Facility Layout

A, B, C & D are the four production lines

Blockages in silos and hoppers are common operational problem. Two frequent cases are Arching/Bridging, where powder forms a stable arch above the discharge outlet, and Ratholing/Channeling, where a vertical channel is created, leaving surrounding material stagnant. Other blockages types include Doming, Caking, Plugging, and Residue build-ups [29], [30].

Figure 3 summarizes explosion incident in factory X and how the Dust Pentagon developed, and mind map in **Figure 4** shows the effects of explosions on different aspects, while **Figure 5** shows the main explosion zone under wheat flour bins.

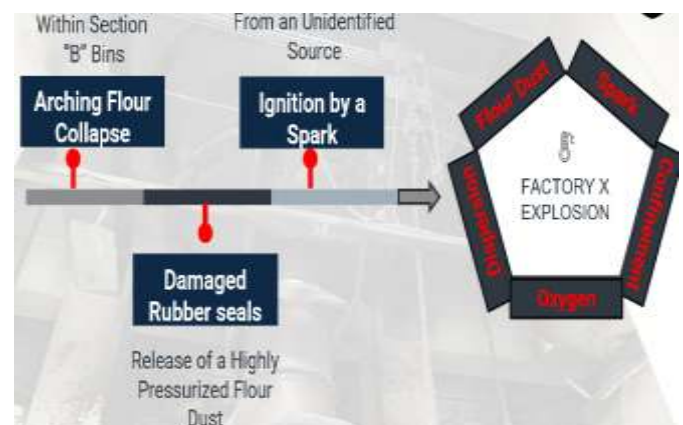


Figure 3 Explosion incident in factory X and the developed Duat Pentagon

concrete compressive strength. Based on established research, concrete exposed to temperatures below 350 °C typically retains 85-100% of its original compressive strength, and the elastic modulus reduction at this range is estimated at approximately 15-25%. Reinforcement steel properties would remain essentially unaffected at these temperatures [8], [11], [12] (**Figure 6**) (**Figure 7**).

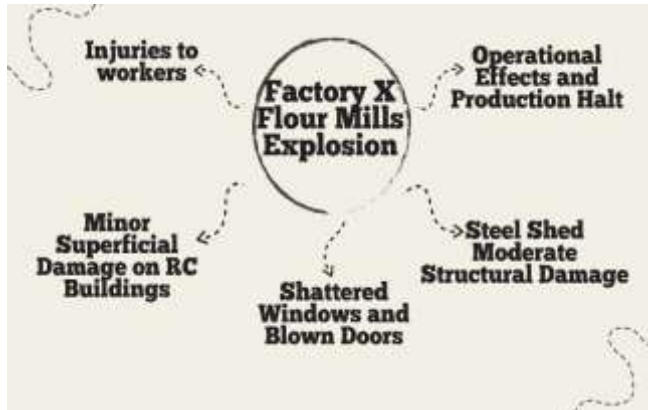


Figure 4 Mind map representing the Factory X explosion effects



Figure 5 Wheat flour bins at section B (Explosion Zone)

4.2 Case Study 2: Residential Building (Loadbearing Masonry with RC Elements)

The Fire incident occurred at two storey load-bearing residential house (Constructed on 1989) located in

Table 1: Post-Fire Damage Assessment Summary for Factory X [25][31][32]

Category	Indicator	Location / Zone	Implication/VITI
RC	Plaster crack at RC Column supporting the bins (Figure A .3)	Column which supporting the bins	Plaster detached, underlying concrete unaffected by any kind of cracking or spalling and the concrete colour was normal grey colour, temperature in this area most likely not more than 300 °C . (This observation coincides with the RHT and UPV results carried out by UKCC team)
	Concrete colour remained grey, limited superficial spalling (Figure A .1)	RC slabs and columns near blaze zone	Plaster Spalling (Table A. 1)(Table A. 2) and didn't exceed to surface spalling in concrete member, and all members were intact. The concrete colour underneath the plaster was normal grey colour. No major strength loss, temperature in this area most likely not more than 300 °C .
Non-Metallic	Polycarbonate fluorescent light fixture cover softened/melted (Figure A .2)	Distributed throughout the facility	Polycarbonate flows above 155 °C, melts ~320 °C (Table A. 4), the fire did not reach plastics ignition point ~580°C, temperature in this area most likely not more than 320 °C .
	Polypropylene (PP) packing bags and plastic crates were melted. (Figure A .5)	Packing/Storage areas	PP Bags melting point was reached (~160-170 °C), plastic melting point was reached (~65-205 °C) (Table A. 4); No flour ignition (Minimum Ignition Temperature MIT ~430 °C). Temperature hit these flour bags was most likely below 430 °C as the fire blaze temperature did not reach the MIT of flour dust.
Paint/ Finishes	Paint blistering, soot and bubbles (Figure A .3)	Concrete members near the flour bins	Paint destroyed at ~150 °C (Table A. 4); soot deposits indicate fire exposure; there was no evidence of any crazing or concrete spalling, which indicate that structural integrity of the concrete was not degraded by the fire; temperature in this area most likely not more than 150 °C.

Jabra, Khartoum State, Sudan. The incident took place on M As a result of applying VITI the fire temperature during the incident was most likely did not exceed the range of 350-400 °C. Therefore, at temperatures below 400 °C, concrete is expected to retain approximately 80-100% of its compressive strength, with the elastic-modulus reduced by roughly 20-30%. Reinforcement steel yield strength remains largely unaffected below 400 °C [8], [11], [12]. No brick spalling or collapse was observed, indicating that load-bearing integrity of the structural walls likely remains intact, however superficial finishes and some RC elements require repair. It should be noted that the residential case study relies primarily on photographic and visual evidence without supplementary NDT verification. This limitation reflects real-world emergency assessment conditions where immediate NDT may not be available, and the findings should be treated as preliminary until further testing can be performed.ay 2024, during the ongoing conflicts in Sudan due to Unknown fire source and then spread to different parts of the house. **Figure 8** shows the layout of the residential house ground floor.

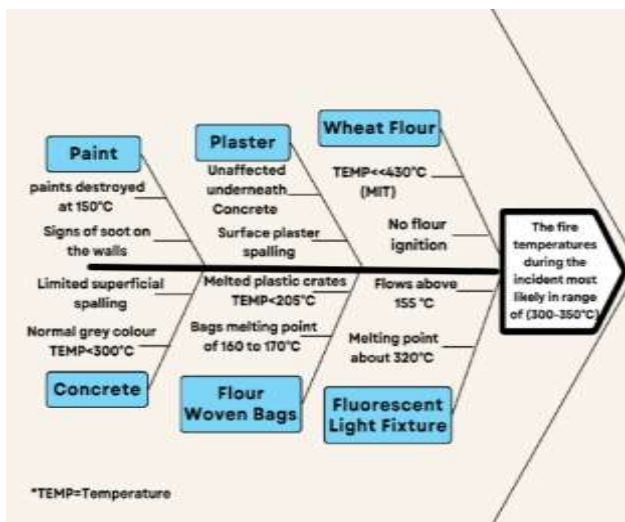


Figure 6 Fish bone analysis of possible fire temperature during the Factory X fire incident

Figure 9 illustrates the ground floor layout of the affected residential building in Jabra, Khartoum and highlights the spread of fire effects. The concentric red circles represent decreasing heat intensity from the assumed fire origin point on Hall B, with areas such as Room 2, the Kitchen, Room 3 and the steel door area suffering higher fire exposure based on observed damage mentioned before.

5. DISCUSSION

The two case studies in this research show that VITI analysis method is a useful way to figure out the temperature and condition of a structure after a fire or explosion incidents.

The correlation between changes in materials and estimated temperature ranges, which was validated against established guidelines and supporting evidence, shows that this method is reliable for initial structural evaluation.

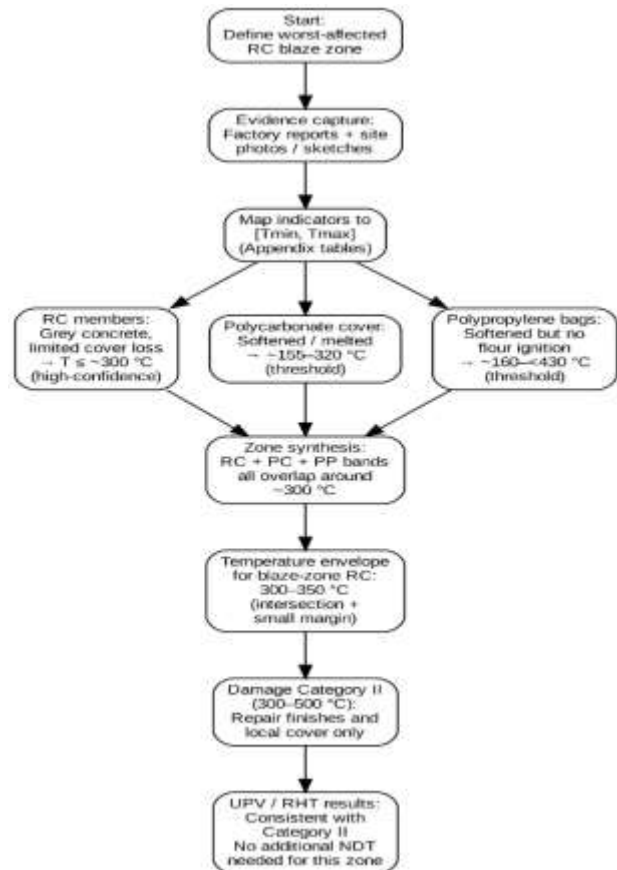


Figure 7 Factory X VITI decision flow



Figure 8 Layout of the residential house ground floor

The Factory X case study supports the methodology validation through the existence of professional assessment data and non-destructive testing outcomes done by UKCC. The temperature estimates obtained from VITI analysis method, align with the findings of the

professional assessment, validating that temperature remained within the 300-350 °C range and that structural integrity was maintained.

The residential case study showed how the methodology can be applied in situations where comprehensive professional evaluation may not be immediately

Table 2: Post-Fire Damage Assessment for the Residential Building

Category	Indicator	Location/zone	Implication/VITI
RC Mem- bers	RC slab spalling, ex- posed aggregate and re- inforcement; whitish patches (Figure A .9- Figure A.10)	Room 3 Slab	Medium spalling (Table A. 1); moderate damage (Table A. 2). Whitish patches are interpreted as likely durability-related (pre-existing moisture ingress, carbonation, or salt deposits) rather than fire-induced discolouration. This interpretation is supported by the following observations: (1) the whitish patches are localised and not uniform across the fire-exposed area, which would be expected if caused by high-temperature exposure above 600 °C; (2) the surrounding concrete retains its original grey colour with no pink or red discolouration indicative of 300-600 °C exposure; (3) visible reinforcement corrosion in these areas suggests long-term moisture presence. However, the authors acknowledge that literature often associates whitish/grey concrete with high-temperature exposure (above 600 °C), and this interpretation requires confirmation through supplementary testing such as the phenolphthalein indicator test or core sampling, temperature in this area may have locally reached or somewhat exceeded 300 °C . ³⁴
	Corroded reinforcement noted around spalled regions (Figure A .9 - Figure A.10)	Room 3 Slab	Interpreted as pre-existing durability problem (Moisture/Carbonation), likely contributed to spalling extent (Table A. 5) (Table A. 6), but there is no change in slab concrete colour, temperature in this area was most likely not more than 300 °C .
Masonry (Brick & Mortar)	Exposed brick masonry intact with plaster spalling (Figure A .7)	Room 3 Walls	Plaster spalling only; bricks intact (no missing outer corners), damage largely cosmetic. Bricks start to lose strength when exposed to temperatures between (~200-400 °C) (Table A. 4), temperature in these areas was most likely not more than 400 °C .
	Discoloured mortar joints (Dark brown) (Figure A .8)	Room 3 Walls	Mortar colour changes consistent with elevated temperatures. Between (~300-400 °C) (Table A. 4) mortar colour may turn into dark brown, temperature in these areas was most likely not more than 400 °C .
	No brick spalling or wall collapse observed	General (Ground floor)	Load-bearing masonry integrity likely retained.
Metal Compo- nents/ Fin- ishes & Coatings	Bubbled/peeled paint with soot on the walls (Figure A .6 ; see also Figure A.11)	Steel door area/ Area between Room 1&2	Paints destroyed at ~150 °C (Table A. 4), the top part of doors usually collects hot gases during fire incidents. Temperature in these areas most likely not more than 150 °C .
	Steel door with coating deterioration; surface oxidation visible (Fig- ure A.11)	Steel door area	Paint/Powder coat (usually Polyester/Epoxy-based powder) blistered/peeled (Occur at~250-300 °C), steel intact and structurally sound (steel has no strength reduction up to 400 °C at which surface oxidation (Rust) begins). Temperature in this area most likely not more than 400 °C .
	Metal grill & window frame with soot de- posit, no distortion (Figure A.12)	Window opening area	Small/thin soot layer; no bending/deformation, no rusting, steel did not reach its melting or oxidation point (No Rusting), temperature was hot enough to destroy paint but did not affect small steel section. Temperature in this area most likely not more than 400 °C .
Electrical/ Plastic Fixtures	Ceiling fan with visible soot; blades straight; plastic parts intact (Figure A .13)	Room 1 (ceiling)	No apparent distortion, did not reach plastic melting point (~65-205 °C) (Table A. 4), temperature in this area most likely not more than 205 °C .

	Melted electrical switch cover (Plastic) (Figure A .14)	Kitchen area	Plastic melting point was reach (~65-205 °C) (Table A. 4); Temperature in this area most likely not more than 205 °C .
Others	Kitchen walls with exposed bricks; fallen plaster/tiles; extensive finish loss (Figure A .15)	Kitchen	Pattern more consistent with sudden loading (Pressure wave) followed by fire; possible gas cylinder (Unconfirmed).
	Room 2 with plaster & paint damage (photos from video only) (Figure A .16)	Room 2	Insufficient clear photos; authors recommend further assessment and site verification.

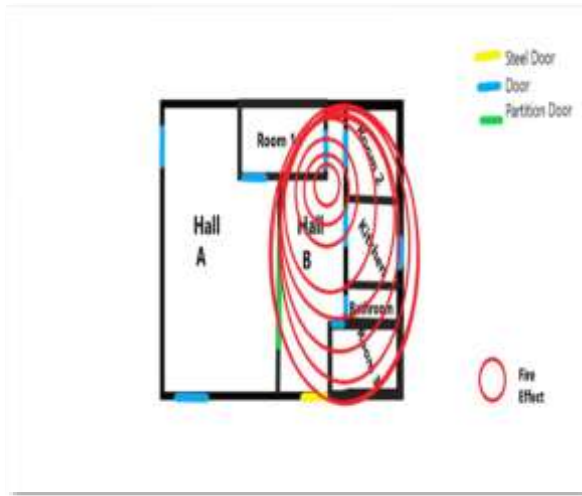


Figure 9 Fire and heat exposure zones in the Jabra Residential Building ground floor layout

available, illustrating the practical value of this approach for rapid initial evaluation.

Both case studies confirm that the correlations between concrete colour changes, other materials degradation patterns and temperature exposure provide a reliable basis for assessment, whilst showing the need of evaluating multiple indicators to increase accuracy and confidence of assessment.

The VITI methodology proposed in this study provides significant practical advantages for structural assessment in environments with limited resources. The method needs basic documentation equipment and trained personnel can perform it without advanced testing equipment, which makes it useful for developing countries and emergency protocols. In real-world applications where information may be limited, such as during rapid post-fire or post-conflict inspections, the VITI methodology provides a structured decision-making framework even when some visual indicators are unclear, conflicting, or missing. In such cases, the methodology directs the assessor to adopt conservative temperature estimates, flag zones requiring further investigation, and recommend targeted NDT for critical mem-

bers. This conservative approach ensures that safety is not compromised when visual evidence is incomplete.

The methodology establishes a cost-effective systematic approach for initial structural assessment which enables decision support for immediate safety measures, potential repair needs and further detailed evaluation requirements. The research findings are crucial for post-disaster situations because they enable rapid assessment of multiple structures.

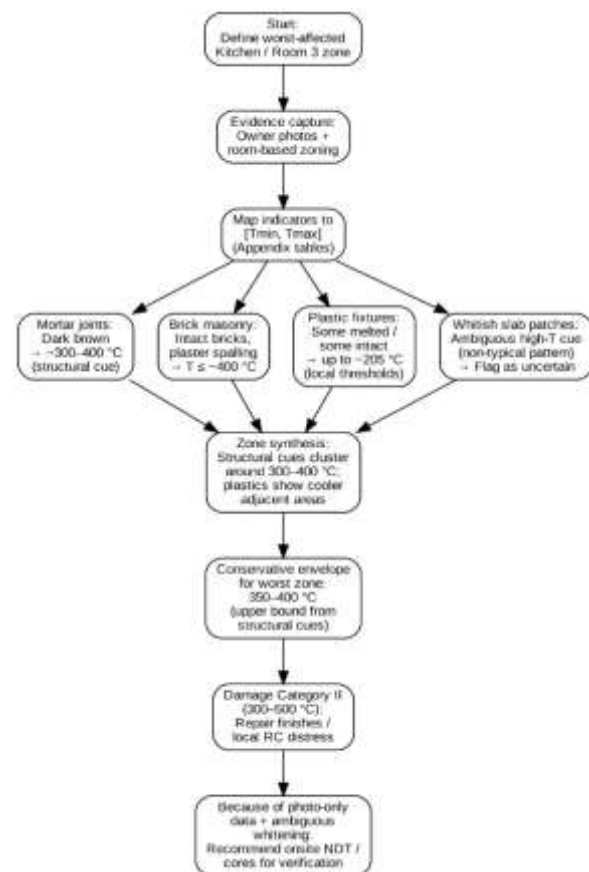


Figure 10 Residential Building VITI decision flow

The VITI methodology is designed to function within a hierarchical assessment framework (visual inference → targeted NDT → selective destructive testing). As demonstrated in the Factory X case study, the

temperature bounds inferred through VITI were consistent with subsequent UPV and RHT measurements conducted by UKCC, confirming the utility of VITI as a reliable first-level screening tool. For the residential case study, where NDT was not available, VITI provided actionable preliminary conclusions that can guide future targeted testing. In practice, zones classified as Category II or higher through VITI analysis should be prioritised for UPV testing (to assess internal concrete quality), Rebound Hammer testing (for surface hardness), or pull-off tests (for bond strength evaluation), particularly for critical structural members.

The VITI analysis methodology provides important practical advantages, but it has specific limitations and application constraints. The accuracy of temperature inference depends on the relationship between materials observable changes and actual temperature exposure, which can be influenced by exposure duration, concrete composition and environmental conditions.

The methodology works best as an initial assessment tool but needs additional evaluation methods for critical structures or complex damage scenarios. The approach provides useful preliminary assessment guidance but is not intended to replace detailed structural analysis for critical or heavily damaged structures. Rather, VITI informs rapid decision-making and prioritises areas requiring more comprehensive evaluation using NDT or destructive testing methods when such services become available.

The correct interpretation of material degradation patterns needs trained professionals who have knowledge of structural behaviour and material properties, experience to make proper assessments and draw accurate conclusions.

The study demonstrates that systematic documentation combined with multiple indicator validation improves the reliability of assessment conclusions. The methodology works best when it is part of a full assessment framework rather than being used on its own.

CONCLUSION

This research presents the Visual Indicator-Based Thermal Inference (VITI) methodology, a practical and cost-effective preliminary approach for post-fire structural assessment. VITI correlates observable material degradation with temperature exposure, offering a systematic framework for initial structural evaluation, particularly in resource-limited settings. The method is based on limited case study data and requires substantial future validation across a wider range of structural types, fire exposure severities, and construction materials before it can be considered a fully validated assessment standard.

The two case studies demonstrate the practical effectiveness of the methodology across different structural types and incident scenarios. Factory X illustrates the application to industrial reinforced concrete structures, whilst the residential case study demonstrates applicability to mixed construction systems. Both cases confirm the reliability of temperature inference through material degradation analysis and validate the correlation between observable changes and structural condition.

Future research should focus on:

- (1) Expanding the validation of the methodology through additional case studies encompassing wider temperature exposure ranges (including high-temperature scenarios above 500 °C), diverse structural types, and various aggregate and concrete compositions.
- (2) Developing standardised protocols and training guidelines for field implementation.
- (3) Investigating the systematic integration of VITI with NDT methods within a formalised hierarchical assessment framework.
- (4) Incorporating supplementary techniques such as the phenolphthalein indicator test for depth-of-damage estimation.
- (5) Quantifying the uncertainty bounds associated with each visual indicator to improve the precision and reliability of temperature inference.

The authors acknowledge that the current findings are based on two case studies at relatively low temperature ranges (below 400 °C), and further work is needed to validate the methodology at higher temperature exposures and across a broader range of building materials and structural configurations.

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Figure A .4: Destroyed paint of concrete members adjacent to flour bins [24]

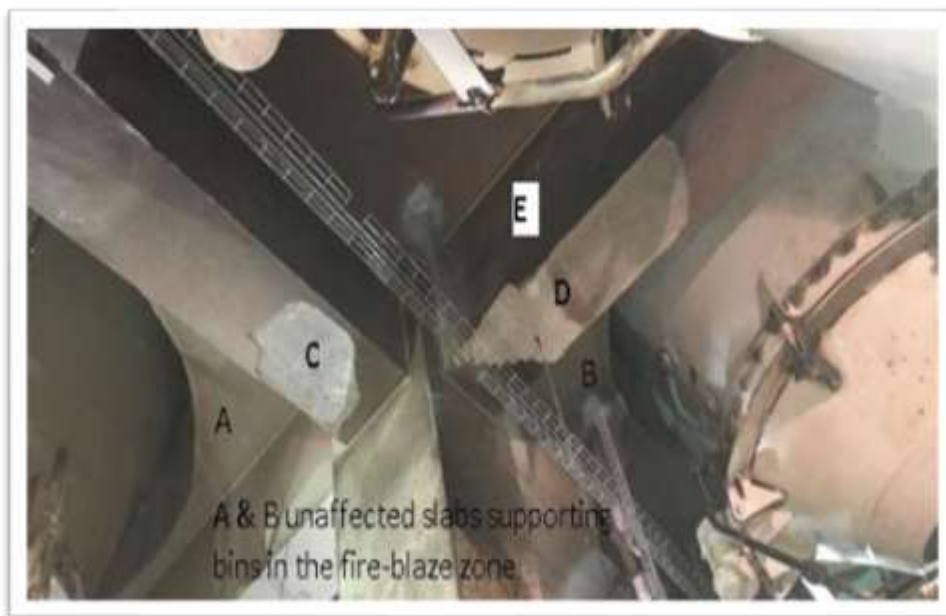


Figure A .5: General view for the fire-blaze zone [25] A and B the unaffected slabs supporting flour bins; C & D exhibited spalled plasters of beams; E shows the black soot on the plaster [31]

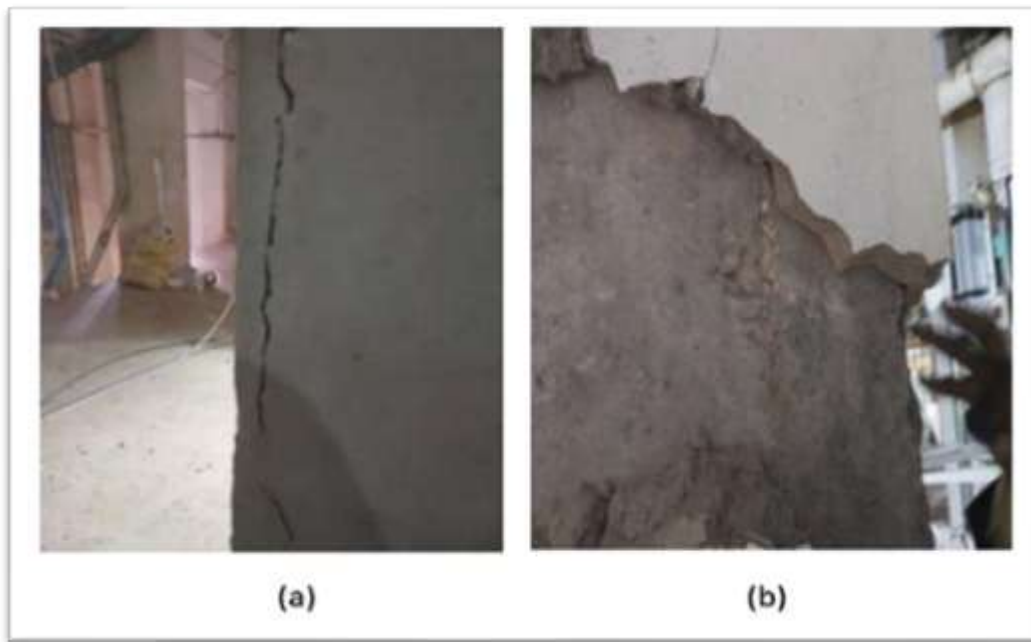


Figure A .6: Plaster crack at RC Column supporting the bins [25]
(a) before removal of plaster; (b) after removal of plaster to ensure the RC column that shows the structural concrete is intact [31]



Figure A .7: Melting without ignition of the lamps plastic cover [25]



Figure A .5: Melted crates and wheat woven bags without flour ignition [25]



Figure A .6: Bubbled paint with soot above the steel door



Figure A .7: Exposed brick masonry with relatively intact structure and plaster spalling at different parts inside room 3



Figure A .8: Discoloured mortar joints in brick walls of room 3



Figure A .9: Spalling occurred in RC slab in room 3



Figure A .10: RC slab with localized spalling and visible patches of whitish discoloration in room 3



Figure A .11: Metal door with maintained overall integrity and coating deterioration



Figure A.12: Metal grill and window frame with soot deposit with no distortion



Figure A .13: Ceiling fan mounted at the centre of the room 1 with visible soot but no apparent distortion



Figure A .14: Melted electrical switch cover in kitchen area



Figure A .15: Kitchen area showing significant structural damage with characteristics most likely consistent with explosion and fire effects



Figure A .16: Photos captured from video of room 2 showing plaster and paint damage with further assessment needed

Table A. 7: Spalling damage classifications. Adapted from [1]

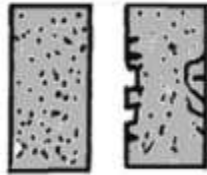
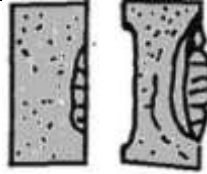
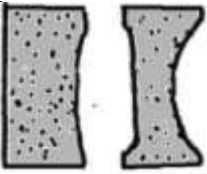
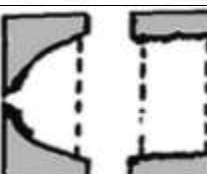
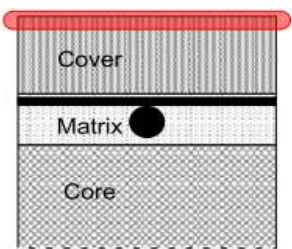
Damage state	Damage description	Scheme of damage
No damage	From no change in the condition of the member to a few barely visible cracks	
Threshold spall	From a few cracks and a hollow sound to a large bulge in the concrete with a few small pieces on the member	
Medium spall	From a very shallow spall to third of the thickness	
Severe spall	From just over one third the thickness to almost breach	
Breach	From small hole which barely allows light through to a large hole	

Table A. 8: Classification of RC element cross section damage degree during fire. Adapted from [14]

Damage degree	Affected part of cross-section	Illustration	Features observed
1	Surface thin layer		• Minor crazing – mesh like fissures with normal concrete colour • Spalling is non-visible • Rebars are non-visible

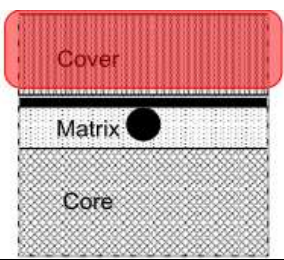
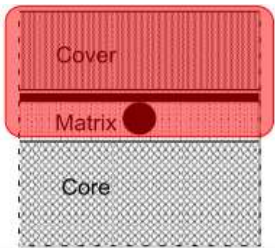
2	Concrete cover		• Moderate crazing - mesh like cracks • Surface spalling • Aggregate spalling Change of concrete colour (pink or red) • Rebars are non-visible or locally visible at places with insufficient cover (up to 25%)
3	Concrete matrix		• Extensive crazing • Corner spalling and cracks along rebars • Sloughing off spalling • Change of concrete colour (pink/red/whitish grey) Up to 50% of rebars are visible • Loss of concrete strength Minor deflection of RC elements
4	Concrete core		• Deep extensive spalling • More than 50% of rebars are visible • Change of concrete colour (whitish grey/buff) -Possible melting of concrete (long-lasting fires) Inner delamination of concrete • Impaired bond between concrete and rebars • Increase of deflection of RC elements • Reduction of rebars mechanical properties • Possible buckling and breaking off of rebars

Table A. 3: Guideline for relationship between concrete colour and strength. Adapted from [18]

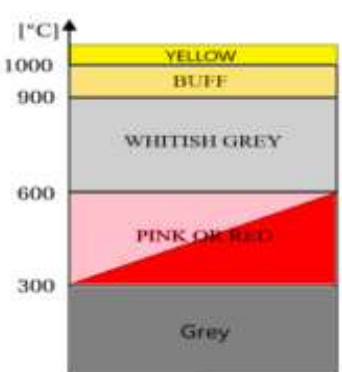
Exposure Temperature	Concrete Colour	Strength Reduction	
Above 1000 °C	Yellow	Complete decomposition of the cement paste	
900 to 1000 °C	Buff	85 to 100%	
600 to 900 °C	Whitish Grey	55 to 85%	
300 to 600 °C	Pink or Red	0 to 55%	
0 to 300 °C	Unchanged	Unchanged	

Table A. 4: Effect of elevated temperature on common construction materials [12], [3], [15], [16], [17].

Substance	Typical examples	Conditions	Approximate temperature (°C)
Paint	-	Deteriorates	100
		Destroyed	150
Polystyrene	Thin-wall food container foam, light shades, handles, curtain hooks, radio casings	Collapse	120
		Softens	120-140
		Melts and flows	150-180

Polyethylene	Bags, films, bottles, buckets, pipes	Shrivels	120
		Softens and melts	120-140
Polymethyl methacrylate	Handles, covers, skylights, glazing	Softens	130-200
		Bubbles	250
Polyvinyl chloride (PVC)	Cables, pipes, ducts, linings, profiles, handles, knobs, house ware, toys, bottles (Values depend on length of exposure to temperature.)	Degrades	100
		Fumes	150
		Browns	200
		Charring	400-500
Cellulose	Wood, paper, cotton	Darkens	200-300
Wood		Ignites	240
Solder lead	Plumber joints, plumbing, sanitary installations, toys	Melts	250
		Melts, sharp edges rounded	300-350
		Drop formation	350-400
Zinc	Sanitary installations, gutters, downpipes	Drop formations	400
		Melts	420
Aluminium & alloys	Fixtures, casings, brackets, small mechanical parts	Softens	400
		Melts	600
		Drop formation	650
Glass	Glazing, bottles	Softens, sharp edges rounded	500-600
		Flowing easily, viscous	800
Silver	Jewellery, spoons, cutlery	Melts	900
		Drop formation	950
Brass	Locks, taps, door handles, clasps	Melt (particularly edges)	900-1000
		Drop formation	950-1050
Bronze	Windows, fittings, doorbells, ornamentation Edges	Rounded	900
		Drop formation	900-1000
Copper	Wiring, cables, ornaments	Melts	1000-1100
Stainless steel	Doors handle, cladding	Melts	1,400-1,530
Cast iron	Cast iron Radiators, pipes	Melts	1100-1200
		Drop formation	1150-1250
Brick	Walls	Solid clay	Deterioration
		Hollow clay	Deterioration