Høgskulen på Vestlandet

ING5002D - Master Thesis

ING5002D-MOPPG-2023-HØST-FLOWassign

Predefinert informasjon

Startdato:	01-12-2023 12:00 CET	**Termin:**	2023 HØST
Sluttdato:	20-12-2023 14:00 CET	**Vurderingsform:**	Norsk 6-trinns skala (A-F)
Eksamensform:	Masteroppgave		
Flowkode:	203 ING5002D 1 MOPPG 2023 HØST		
Intern sensor:	(Anonymisert)		

Deltaker

Kandidatnr.:	103

Informasjon fra deltaker

Antall ord *:	21086

Egenerklæring *: Ja

Jeg bekrefter at jeg har registrert oppgavetittelen på norsk og engelsk i StudentWeb og vet at denne vil stå på vitnemålet mitt *: Ja

Jeg godkjenner avtalen om publisering av masteroppgaven min *

Ja

Er masteroppgaven skrevet som del av et større forskningsprosjekt ved HVL? *

Nei

Er masteroppgaven skrevet ved bedrift/virksomhet i næringsliv eller offentlig sektor? *

Ja, SOCOTEC UK

Assessing the Efficacy of Open-State Cavity Barriers with improper installation through intermediate-scale testing

SARATH GOPI CHERUKAT

WESTERN NORWAY UNIVERSITY OF APPLIED SCIENCES

Master Thesis in Fire Safety Engineering

Haugesund
[02 January 2024]

Assessing the Efficacy of Open-State Cavity Barriers with improper installation through intermediate-scale testing

Master thesis in Fire Safety Engineering

Author: Sarath Gopi Cherukat	Author sign.
Thesis submitted: Fall 2023	Open thesis
Tutor: Bjarne Christian Hagen External tutor: No External Tutor	
Keywords: Open State Cavity Barrier Efficacy in workmanship Facade Fire	Number of pages: 103 + Appendix: 2 Haugesund, 02, January, 2024 Place/Date/year

This thesis is a part of the master's program in Fire Safety engineering at Western Norway University of Applied Sciences. The author(s) is responsible for the methods used, the results that are presented, the conclusion and the assessments done in the thesis.

Preface

This document presents a scientific examination of external wall fire safety, inspired by incidents such as the Grenfell Tower fire in 2017 and the subsequent introduction of the Fire risk appraisal for external wall (PAS 9980). Focusing on the critical role of open-state cavity barriers, our collaborative research project, involving Western Norway University of Applied Science and SOCOTEC UK with support from SIDERISE UK, aims to assess the impact of faulty cavity barrier installations in different scenarios.

By conducting site visits and analysing intrusive survey reports on external walls, the major defective installation methods of Open State Cavity Barriers (referred to herein as OSCB) were identified. By testing six scenarios that simulate potential high impacts on the external wall fire, this study revealed the vulnerabilities within these OSCB. From gaps between barriers to blockages, increased cavity sizes, and corner configurations, the findings emphasize the significance of good workmanship in achieving the necessary level of fire protection.

This document also delves into a global attention for the building safety, addressing incidents like the Address Downtown Hotel fire in Dubai (2015) and the World Trade Centre fire in Doha (2020). While acknowledging the commendable step forward with PAS 9980:2022, a notable research gap in the quantitative analysis of OSCB prompts a collaborative research project to enhance understanding.

Throughout this document, the issues observed during on-site visits and consultations were depicted, offering a detailed examination of challenges related to the installation of OSCB. Visual representations and figures provide tangible evidence crucial for recognizing complexities and informing strategies for improvement.

In conclusion, this report contributes to the scientific discourse on external wall fire safety by providing an in depth understanding to analyse and understand the consequences of various efficacies in the installation of the OSCB and calling for continued research to ensure the safety of communities worldwide.

1 Acknowledgment

I express my heartfelt gratitude to Western Norway University of Applied Science for providing the academic platform that enabled the realization of this thesis. A profound acknowledgment is extended to the Department of Fire Engineering for their unwavering support and provision of essential resources throughout the entire research process. The department's commitment to fostering an environment conducive to academic inquiry has been indispensable in shaping the trajectory of this study. Their collaborative spirit, expert guidance, and dedication to the advancement of fire engineering have significantly enriched the depth and quality of this research. I am deeply appreciative of the department's role in creating a conducive scholarly atmosphere, which has been instrumental in the successful completion of this thesis. I am deeply indebted to Associate Professor Bjarne Christian Hagen, my supervisor, for his invaluable guidance and mentorship.

I extend my sincere gratitude to Thomas Carpentier, Director of Engineering, SOCOTEC UK and Eddy Khoury, Associate Director of Fire Engineering, SOCOTEC UK for their sponsorship, which played a pivotal role in the successful completion of this thesis. The technical and financial support from them significantly contributed to the research. Furthermore, I would like to extend my thanks to Ashish Kirori and Karla Sandoval from SOCOTEC UK for their support throughout the thesis work. This collaboration underscores the importance of industry partnerships in fostering academic pursuits and advancing the field of fire engineering. I am truly appreciative of SOCOTEC UK's commitment to supporting academic endeavours and their invaluable contribution to the fruition of this research project.

I wish to express my heartfelt gratitude to Chris Mort, the Director of Testing at Siderise Group, whose invaluable contribution played a pivotal role in the successful execution of the experimental work for this thesis. Mr. Mort's generosity in providing the essential materials exemplifies the commitment of Siderise Group to supporting research and development initiatives. The steadfast support from Siderise throughout this project has been instrumental, and I am truly grateful for their collaborative and encouraging approach to advancing scientific exploration.

I extend my sincere appreciation to my friends, Vamsidhar Upadhyay, Dheeraj Dilip, Gambhir Paudel, and Ankush Jassal, whose unwavering moral support and collaborative efforts in the laboratory significantly contributed to the successful setup and installation of experiments.

Finally, I am profoundly grateful to my family, especially my Mom and Dad, whose unwavering support, encouragement, and understanding have been instrumental throughout this academic journey.

Abstract

The tragic Grenfell Tower fire in 2017 was worsened by combustible materials within the building structure. Following this incident, Fire risk appraisal of external wall construction and cladding of existing blocks of flats – Code of practice (PAS 9980) was introduced to conduct risk-based fire assessments in existing buildings, evaluating aspects such as fire performance, façade configuration, and fire safety strategy. However, PAS 9980 lacks clear criteria for assessing deficiencies in wall systems, both with and without fire barriers. There is limited research on open-state cavity barrier configurations, hindering comprehensive understanding. A collaborative project involving Western Norway University of Applied Science and SOCOTEC UK with the support of SIDERISE UK aims to evaluate the impact of faulty cavity barrier installations identified in different scenarios.

By conducting site visits and utilizing data from intrusive survey reports on external walls, major defective installation methods in existing buildings were identified. Six different scenarios, posing potential high impacts due to improper installation of open-state cavity barriers, were tested on an intermediate scale. These scenarios include gaps between two blocks of cavity barriers, blockages in front of cavity barriers, increased cavity size, and performance of cavity barriers in the corners of external wall.

Results from the study revealed that gaps larger than 30 mm allowed fire to propagate to the upper compartment. Blockages up to 50 mm in front of cavity barriers prevented temperature rise and flame propagation to the upper compartment with a time delay in the reduction in temperature. An increased cavity gap, surpassing the prescribed limit for the cavity barrier in accordance with manufacturer guidelines by up to 50%, resulted in a proportional extension of the closure time of the cavity by 20-30%. This extension significantly contributed to the prevention of flame propagation and temperature elevation in the upper compartment, demonstrating the efficacy of the modified configuration. In the case of corners, improper closure of the cavity was primarily attributed to the lack of intumescent material. However, the temperature in the upper compartment adhered to the guidelines required by TGD19.

The findings of this investigation underscore the significance of workmanship in the construction of wall envelope compositions to attain the necessary level of fire protection. The conclusion of the study emphasizes that disruptions in the consistency of cavity barriers during on-site installation represent a crucial factor that demands careful consideration. The paper suggests an approach for evaluating and understanding the implications of such incidents within the specified wall envelope configuration.

Summary

This document presents a scientific examination of external wall fire safety, inspired by incidents like the Grenfell Tower fire, focusing on the critical role of open-state cavity barriers (OSCB). The collaborative research project, involving Western Norway University of Applied Science and SOCOTEC UK, aims to assess the impact of faulty cavity barrier installations in different scenarios. Major defective installation methods of OSCB were identified through site visits and survey reports. The study tested six scenarios simulating potential high impacts on external wall fires, revealing vulnerabilities in OSCB installations such as gaps, blockages, increased cavity sizes, and corner configurations. The findings underscore the importance of good workmanship for effective fire protection. The report also addresses global incidents and acknowledges the positive step of PAS 9980:2022 while emphasizing the need for quantitative analysis of OSCB.

In conclusion, the research compares Scenario 1 (OSCB installed according to guidelines) with Scenarios 2 to 7, assessing the impact of deviations on fire and smoke propagation. Larger gaps between OSCB blocks were found to increase fire spread risk. Blockages in front of intumescent strips and larger cavities demonstrated challenges in cavity closure. Scenario 7 at corners revealed incomplete closure, suggesting a need for optimal installation practices. The analysis provides valuable insights into OSCB efficiency in various scenarios, contributing to fire safety understanding and identifying areas for further exploration and improvement.

Contents

Table of figures

Tables

Definition

Terms	Definition
Performance-based fire safety design	Deign that is engineered to achieve specified fire safety design objectives based on performance criteria.
Prescriptive regulation	Regulation in which the means and approach for compliance are completely or mostly specified
Verification	The process of ascertaining compliance with fire safety requirements in a design involves a thorough examination of the design in relation to established safety criteria. This process is also commonly referred to as the evaluation of the design's conformity with fire safety standards, and the term is likewise used to describe the resulting outcome of this evaluation.
Open State Cavity Barrier	A fire safety component designed to prevent the spread of fire and smoke within concealed spaces, such as wall cavities or voids in buildings. Unlike traditional cavity barriers, an open state cavity barrier remains in an open or expanded configuration during normal conditions but activates and closes in the event of a fire.
Integrity	the ability of the barrier to maintain its structural and functional performance under fire conditions.
Insulation	The ability of the barrier to resist the transfer of heat during a fire
NCC	National Construction Code
NFPA	National Fire Protection Association
SFPE	Society of Fire Protection Engineers

2 Introduction

2.1 Background

External wall fires have been a global concern, and several incidents have highlighted the importance of fire safety in building design. One notable example occurred in Dubai, United Arab Emirates, on New Year's Eve in 2015, when a fire engulfed the Address Downtown Hotel [1]. Another significant incident took place in London, United Kingdom, in June 2017, where the Grenfell Tower fire tragically claimed many lives [1]. More recently, in November 2020, a fire erupted in the World Trade Centre building in Doha, Qatar, emphasizing the worldwide impact of external wall fires. [1]. These incidents underscore the need for stringent fire safety measures and regulations in building construction across diverse geographical locations.

Numerous assessment methods for external wall fire safety exist globally, reflecting the diverse strategies implemented to ensure robust building standards. In the United States, the NFPA 285 [2] standard provides guidelines for evaluating the flammability of exterior wall assemblies. The British Standard BS 8414 [3]is widely used in the United Kingdom, involving large-scale fire tests to assess the fire performance of external cladding systems. Australia employs the Deemed-to-Satisfy provisions of the National Construction Code (NCC)[4], which includes provisions for external wall materials and fire resistance. China, too, has its own set of standards, such as GB 8624 [5], which classifies building materials based on their combustibility. These examples illustrate the global variety of external wall fire assessment methods, each tailored to the specific building codes and regulations of the respective regions. The continual development and implementation of such assessment tools contribute to enhancing fire safety practices in construction worldwide.

In numerous countries worldwide, the use of open-state cavity barriers has become a prevalent practice to prevent the spread of fire in external walls. For instance, in the United Kingdom, where fire safety regulations have been under heightened scrutiny following incidents like the Grenfell Tower tragedy, open-state cavity barriers are employed as part of comprehensive fire protection strategies. [1] Australia, guided by the National Construction Code (NCC) [4], similarly emphasizes the installation of open-state cavity barriers in external wall constructions to impede the vertical and horizontal progression of flames. In the United States, the NFPA 285 [2] standard recommends the use of cavity barriers as a critical component for controlling the spread of fire on the exterior of buildings. These examples underscore the global recognition of the efficacy of open-state cavity barriers in mitigating the risks associated with external wall fires, emphasizing their widespread adoption in diverse regulatory frameworks.

2.2 Problem statement

The tragic event that occurred on June 14, 2017, when a devastating fire swept through London's Grenfell Tower, resulting in the heart-breaking loss of 72 lives and causing many injuries and displacements. At the heart of the Grenfell Tower's external structure was a composite system composed of aluminium composite material (ACM) panels, polyisocyanurate (PIR) insulation, and a ventilated cavity. Regrettably, this amalgamation inadvertently contributed to the disaster [6]. The ACM panels, comprised of two thin aluminium sheets with a polyethylene core, proved highly flammable. [1] The PIR insulation was likewise combustible, while the ventilated cavity, initially intended to facilitate air circulation and moisture removal, inadvertently exacerbated the fire's rapid spread by creating a chimney effect [5].

The impact of the Grenfell Tower tragedy rippled far beyond its immediate vicinity, affecting not only its residents but also millions residing in medium to high-rise buildings across the UK and worldwide [6]. In July 2020, a fast-track initiative was launched to develop a PAS (Publicly Available Specification) standard that could furnish fire engineers and other qualified professionals with a methodology for assessing the holistic risk level within a building and subsequently determining the need for remedial actions. This project was executed by the British Standards Institution, sponsored by the Department for Levelling Up, Housing and Communities (DLUHC) and the Home Office, and concluded in July 2021, preceding its official release in January 2022 under the title of PAS 9980:2022 Fire Risk Appraisal of External Wall Construction and Cladding of Existing Blocks of Flats – Code of Practice [7].

However, there is no documents or research area to analyse the effectiveness of OSCB installed with a deviation from the manufacturer guidelines quantitively. The various configurations of existing cavity barriers have received limited research attention, with a scarcity of scholarly papers providing insights into the impact of cavity barriers when they are installed contrary to the manufacturer's recommendations and the tested arrangement.

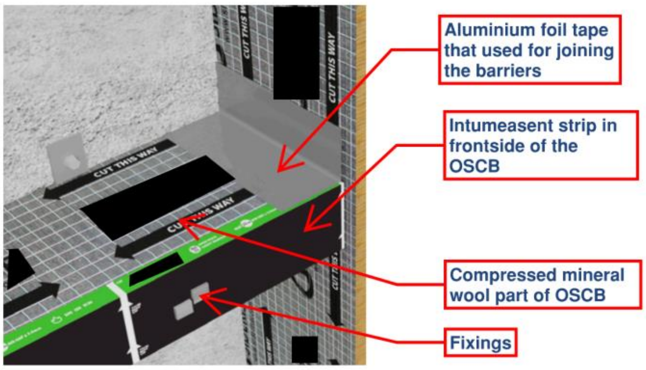


Figure 1 - Open state cavity barrier (OSCB)

As a result, a collaborative research project was developed in partnership with the Western Norway University of Applied Sciences and SOCOTEC UK. This project aims to assess the effectiveness of faulty cavity barriers within wall systems, with the goal of enhancing our comprehension and quantification of various types of defects during the installation of OSCB and their respective influences on cavity barrier performance when subjected to fire exposure. The majorly identified problems that considered as preliminary are:

- Inadequate installation of the fixing brackets, either the number of brackets used not being in accordance with the manufacturers recommendations or the installation being defective;
- Missing cavity barrier
- Cavity barrier in place but sagging in the cavity due to issues with the fixing brackets;
- Gaps between the cavity barriers;
- Cavity barrier connection joints not tapped in accordance with the manufacturer’s recommendation;
- Incorrect dimensional gap between the rear of the cladding panel and the cavity barrier;
- Issues detected in real-time during the site inspection.

3 Literature Review and Construction Site Observations

A global perspective on external wall fire hazards is enriched by research from diverse regions. In the United States, NFPA 285 standards have been pivotal in guiding fire safety assessments for exterior wall assemblies. This standard, as discussed by Shipp et al. [9], provides a comprehensive framework for evaluating the flammability of such assemblies, underlining its significance in a country where large-scale fires in external wall systems can have catastrophic consequences. Meanwhile, the Australian National Construction Code (NCC) incorporates provisions for external wall materials and fire resistance, contributing to the nation's resilience against external wall fire hazards. The research by Daly et al. [10] in Australia draws attention to the importance of supervision in ensuring critical components are installed as per manufacturers' specifications, emphasizing the role of on-site workmanship in fire protection strategies.

In the United Arab Emirates, the Address Downtown Hotel fire on New Year's Eve in 2015 serves as a poignant case study, revealing vulnerabilities in external wall fire safety. This incident, as explored by relevant investigations and discussed in studies such as those by Littlewood et al. [11], emphasizes the need for global attention to external wall fire hazards, transcending geographical boundaries. Furthermore, experiences in Qatar, exemplified by the fire in the World Trade Center building in November 2020, reinforce the importance of robust fire safety measures in rapidly developing regions. This incident, with parallels to the global discourse on external wall fires, underscores the need for a fine understanding of regional contexts and regulatory frameworks to address the diverse challenges posed by external wall fire hazards.

While having a detailed analysis following the Grenfell Tower fire incident, a series of substantial shifts in the focus on the fire safety of buildings emerged in the United Kingdom. This was mainly for the residents of high-rise buildings with hazardous combustible cladding were the first to be affected. The introduction of "waking watches," as defined by the government, entailed the continuous patrol of all floors and the building's perimeter by suitably trained personnel to detect fires, raise alarms, and manage evacuations. This measure, though necessary, led to the employment of fire wardens 24/7, a role traditionally fulfilled by comprehensive fire alarm systems. Such systems were not common in the UK, where the prevailing evacuation strategy had been "stay put," involving the evacuation of only affected residents while the fire brigade handled the situation. This interim solution for unsafe buildings is expected to persist for years, with an average monthly cost of £11,361 per building, based on data from the Ministry for Housing, Communities, and Local Government (MHCLG) in 2020. [8]

The second consequence was felt in the housing market, where the risk of fire insurance claims surged. Insurers grew increasingly concerned about building fire safety, resulting in a reluctance to insure high-rise flats or an inclination to charge higher premiums. Subsequently, lenders hesitated to offer mortgages for flats with uncertain external wall conditions, as buyers might be required to finance future remedial work should the external wall construction prove unsafe. This scenario led to the introduction of the EWS1 form by the Royal Institution of Chartered Surveyors (RICS) and UK Finance in December 2019. Initially applicable to buildings over six storeys or 18 metres in height, this requirement later extended to buildings over 11 metres, aligning with the typical ladder height available on fire engines to support external fire and rescue operations when needed. The certificate is a simple form signed by a qualified professional to confirm whether the external walls are safe and do not need any further action. Or whether remediation is required. [7]
However, with the lack of data or methodology to assess the level of risk on existing buildings with combustible material or defective fire barriers, the conclusion after a façade survey for the majority of existing buildings was that remedial works are required to remove existing combustible materials and to make the buildings compliant with the current Building Regulations.

In July 2020, a fast-track initiative was launched to develop a PAS (Publicly Available Specification) standard that could furnish fire engineers and other qualified professionals with a methodology for assessing the holistic risk level within a building and subsequently determining the need for remedial actions. This project was executed by the British Standards Institution, sponsored by the Department for Levelling Up, Housing and Communities (DLUHC) and the Home Office, and concluded in July 2021, preceding its official release in January 2022 under the title of PAS 9980:2022 Fire Risk Appraisal of External Wall Construction and Cladding of Existing Blocks of Flats – Code of Practice. [7]

PAS 9980 offers a systematic methodology for evaluating the level of life safety risk in existing buildings by scrutinizing three key factors:
1. The Fire Performance of external walls, encompassing an assessment of material combustibility, the presence of cavity and fire barriers, and the construction details of the wall.
2. The Façade Configuration of various wall systems within the building, with a focus on assessing fire spread risk based on location, extent of coverage, ignition potential, and fire spread hazards.
3. The Fire Strategy of the building, encompassing an evaluation of the availability of adequate mitigation measures such as multiple exit staircases, evacuation protocols, sprinkler systems, and fire and rescue access provisions.

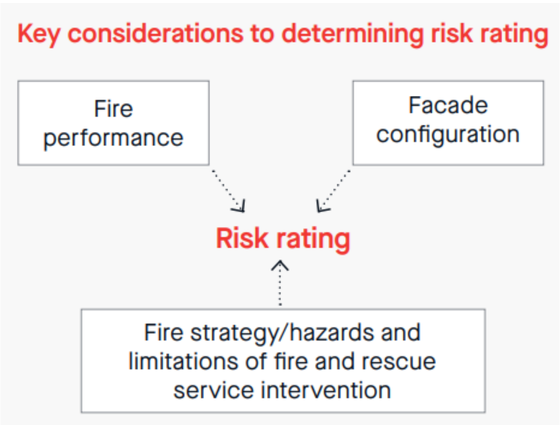


Figure 2 - Source: BSI A guide to PAS 9980– Executive briefing

All buildings are considered to be in the high-risk category at the beginning of the Fire Risk Appraisal process, moving down the order once enough key factors that influence risk are evaluated and determined to be positive influences in order to justify a new band risk category.
The appraisal process is in essence qualitative; but in some special cases may require a more quantitative analysis and performance-based analysis. The PAS 9980 provides guidance for determining the influence of each key factor to support the fire risk appraisal, however, the conclusion remains qualitative and subjective where a competent assessor needs to clearly document their assumptions, evidence, and justification for the final risk classification.
Only buildings with the high-risk category classification will certainly require remedial works, whereas those in the medium-band risk category may only require remedial measures to control the risk.

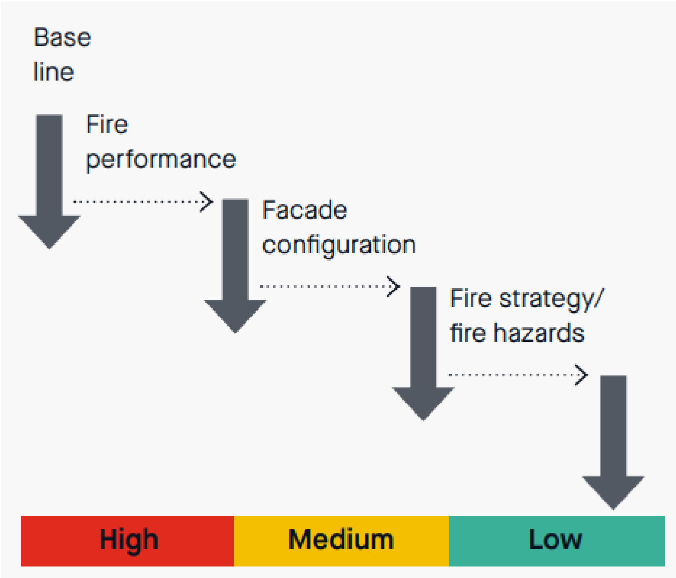


Figure 3 - Source: "Figure 9" of PAS 9980:2022

While PAS 9980 relies on findings from several research studies to help determine the influence of the key factors that influence risks, some of the vital elements that could help determine the fire performance of external walls are still under-researched with little evidence to determine a positive or negative influence. Such element is the cavity fire barriers which are known to be key aspects of the fire performance of walls as seen in many BS 8414 full-scale tests.

Figure 4 - (a) EPS system without fire barriers (b) EPS system with Fire Barriers - Source: BR135:2013

Cavity and fire barriers are usually expected to be installed at the intersection of external walls and compartment floors/walls as well as around openings (windows, doors etc.). [7] The cavity barriers at the intersection of compartment floors and walls are sometimes considered an extension of the floor/slab and therefore should act as firestopping systems and therefore achieve a fire rating equivalent to the compartment floor/wall.

When the fire barrier is within the external wall, it is considered to be a cavity barrier and therefore required to only achieve a fire resistance of 30 minutes (E 30 and EI 15). [14]

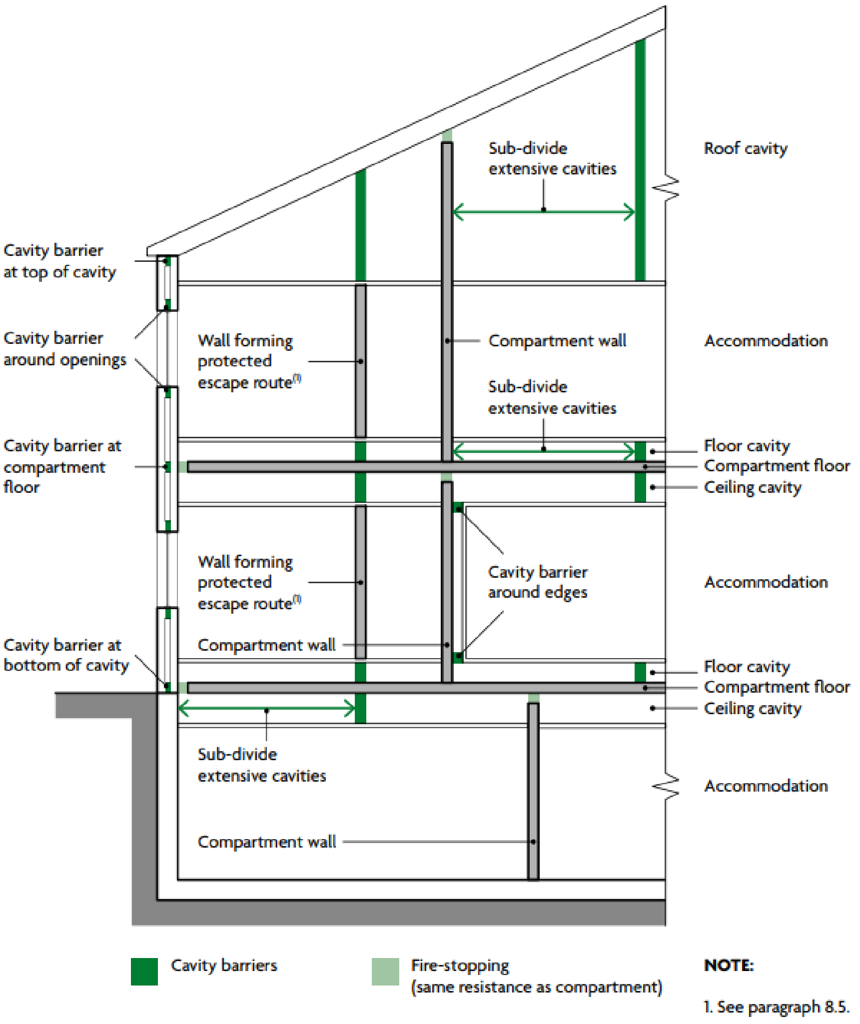
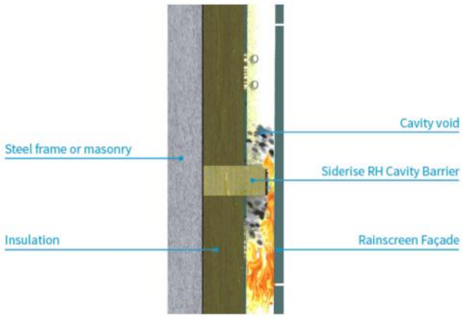


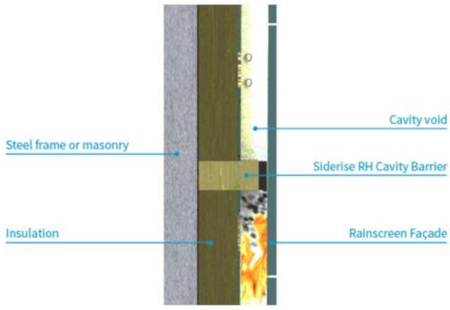
Figure 5 - Cavity Barrier provisions diagram - Source: ADB 2 vol.:2019

There are two main types of cavity fire barriers on Façade systems:

- Closed-state cavity barrier which are usually designed to provide fire separation within or at the edges of a concealed space (cavity) by forming a tight seal (possibly under compression) between the inner and outer surfaces of the cavity.
- Open-state cavity barrier: designed to provide fire separation in a concealed space (cavity), which is open to allow ventilation and drainage in the cold state, but with intumescent materials which closes when exposed to a developing fire. This type is very common on rainscreen cladding systems where ventilation in the cavity is required mainly to improve ventilation and control moisture [17].



(a)



(b)

Figure 6 - Open-State Cavity Barrier (a)During the fire (b) after the intumescent strip expansion – Source Siderise website

To comprehensively address external wall fire hazards globally, it is crucial to consider the multifaceted nature of these challenges. The literature reviewed herein reflects a synthesis of insights from various regions, encompassing issues of detail integrity, regulatory shortcomings, and the pivotal role of workmanship in ensuring fire safety. The identified hazards, drawn from real-world incidents and empirical research, underscore the urgency for a holistic and context-specific approach to external wall fire safety on a global scale.

The construction industry grapples with a pervasive challenge related to the non-conformity of as-constructed detail assemblies with approved technical designs, and one prominent factor contributing to this issue is inadequate workmanship [17]. This complex problem has been extensively scrutinized in the literature, as evidenced by the works of scholars such as Littlewood et al. [12] Hackitt [20], Comiskey et al. [22], and Daly et al. [23]. The Chartered Institute of Building's (CIOB) research highlights concerns regarding the management of workmanship quality, findings echoed by independent inquiries into specific construction projects, including the Edinburgh Schools [24] and the DG One Complex [25]. The paramount importance of high-quality workmanship is widely acknowledged due to its profound implications for preventing the spread of fire [26]. Despite this recognition, a potential gap in awareness exists among unskilled tradespeople, particularly concerning critical aspects of passive fire protection, such as fire and cavity barriers [26]. This lack of awareness may lead to non-compliance with essential detail assemblies.

Scholarly investigations further establish the link between on-site workmanship and its potential repercussions on fire protection strategies. For example, the study by Daly et al. [23]. emphasizes issues with supervision and the apparent oversight of the crucial nature for the installation of components, vital from a life safety perspective, to adhere precisely to manufacturers' specifications. Echoing this sentiment, Littlewood et al. [12] suggest that detail integrity is not assured, and latent deficiencies in the building fabric may contribute to the propagation of smoke and fire. Building on a decade-long research endeavour, the Building Research Establishment (BRE) Global found that, out of approximately 106 investigated fires, 34 had an aspect related to concealed fire spread. Notably, almost half of these cases cited cavity barrier issues, either exclusively or in conjunction with other concerns [9]. This comprehensive body of research collectively underscores the multifaceted nature of the challenges surrounding as-constructed detail assemblies and emphasizes the critical role of stringent workmanship standards in ensuring fire safety in construction practices.

In assessing the effectiveness of cavity barriers, [19] conducted research addressing various issues. They augmented this qualitative analysis with a Failure Mode and Effect Analysis (FMEA) involving building control professionals. This FMEA systematically evaluated the likelihood of diverse potential defects occurring during installation and assessed the severity of the negative impact associated with each hypothetical defect as indicated in the Table 1. The findings from this study underscore the significance of workmanship in the construction of wall envelope compositions to attain the necessary standard of fire protection. The FMEA table formed by David Comiskey et al., [19] was as mentioned below;

Table 1 - The FMEA analysis of the different defects for the cavity barriers

Description of the defect	**Probability (P)**	**Severity (S)**	**Risk (P x S)**	**Risk Level (RL)**
Inadequate installation of the fixing brackets, either the number of brackets used not being in accordance with the manufacturers recommendations or the installation being defective	3	3.5	10.5	Moderate
Missing cavity barrier	3	4	12	High
Cavity barrier in place but sagging in the cavity due to issues with the fixing brackets	3	3.5	10.5	Moderate
Vertical cavity barrier installed in a horizontal position	2	4	8	Low
Horizontal cavity barrier installed in a vertical position	2	1	2	Low
Horizontal cavity barrier installed with a wrong orientation (i.e. upside down)	2	3	6	Low
Gaps between the cavity barriers	4	3	12	High
Cavity barrier connection joints not tapped in accordance with the manufacturer's recommendation	4.2	2	8.4	Low
Cavity barrier placed in front of the insulation. i.e. insulation placed first that is not in accordance with the manufacturer's recommendations.	2.2	4	8.8	Low
Incorrect dimensional gap between the rear of the cladding panel and the cavity barrier.	2	4	8	Low
Cavity barrier material substitution.	2.8	4.2	11.8	Moderate

Table 2 Risk Matrix used for the FMEA Analysis

Severity / Probability	Extremely unlikely (1)	Remote (2)	Occasional (3)	Reasonably possible (4)	Frequent (5)
No effect (1)	1	2	3	4	5
Very minor effect (2)	2	4	6	8	10
Minor effect (3)	3	6	9	12	15
Critical (4)	4	8	12	16	20
Catastrophic (5)	5	10	15	20	25

Low Risk Level
Medium Risk Level
High Risk Level

In light of these risk factors, the subsequent major concerns were taken into account when identifying the significant deviation requiring quantitative assessment through intermediate-scale testing.

PAS 9980 provides a different classification for wall systems with or without fire barriers, however, there are no clear criteria for determining where deficiencies can be considered minor and where these should be considered major and can lead to adverse effects during a fire.

3.1 Identified Issues from the construction site.

Significant challenges related to the installation of open-state cavity barriers were discerned through on-site visits and consultations with facade technical experts and construction personnel, facilitated by SOCOTEC UK. Additionally, qualitative assessments conducted by David Comiskey and Kayleigh Wilson, [19], contribute valuable insights.

Furthermore, in certain locations, were the metal panel rain screen claddings are installed, a workmanship issue is noticed were they forgot to install the open state cassette insert, indicated in the Figure 7, behind the cladding panel in line with the horizontal cavity barrier which allows a proper closure of the cavity during a fire event. The results obtained in this scenario will offer insights into the impact of gap size on the potential spread of fire to the upper compartments.

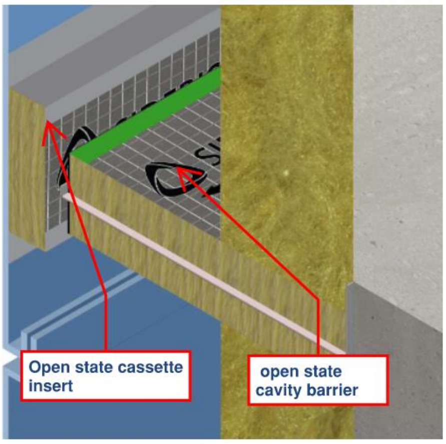


Figure 7 - Open state cassette insert installed behind the metal cladding panel in line with the open state cavity barrier

Based on these compiled information, certain factors were identified as potential critical contributors to the effectiveness of cavity closure by the OSCB during a fire incident. Recognizing these aspects is crucial for enhancing the overall fire safety performance of building facades, the major concerns that were identified as critical from the site are as follows;

- OSCB installed in accordance with Manufacturer Guidelines;
- Gaps between two blocks of the OSCB;
- Blockage created by fixings in front of the OSCB;
- More cavity space in front of the intumescent strip of the OSCB;
- Intumescent strip expansion for the OSCB installed at the corners.

A few figures (Figure 8 to Figure 13) that are obtained from on-site observations, as illustrated below, vividly depict real-time challenges associated with the effective installation of open-state cavity barriers. These visual representations serve as tangible evidence, highlighting practical issues and discrepancies encountered during the installation process at the site. By capturing these figures, the nuanced complexities and potential shortcomings in implementing OSCB become evident, offering a valuable and direct insight into the actual conditions on the ground. In contemplating these prevailing issues, it is noteworthy that there is a lack of comprehensive documentation or research explaining the behaviour of OSCB in such configurations and their efficacy in impeding the progression of fire and smoke to the upper compartment.

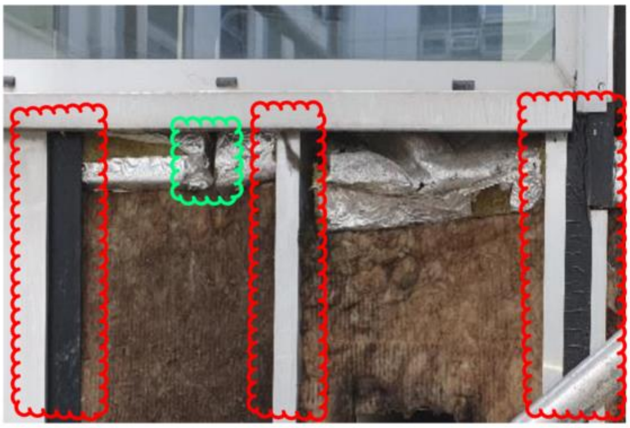


Figure 8 - Blockages in front of the OSCB highlighted in red cloud and the gap between two OSCB highlighted in green cloud

Figure 9 - Gaps or discontinuity for the horizontal open state cavity barrier

Figure 10 - Loosely packed cavity barriers with blockages in front of the intumescent strip highlighted in red cloud

Figure 11 - Blockages in front of the cavity barrier highlighted in red colour

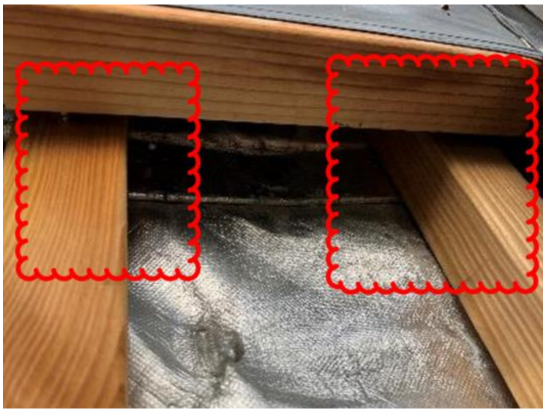


Figure 12 - Compressed intumescent strips behind the wooden battens

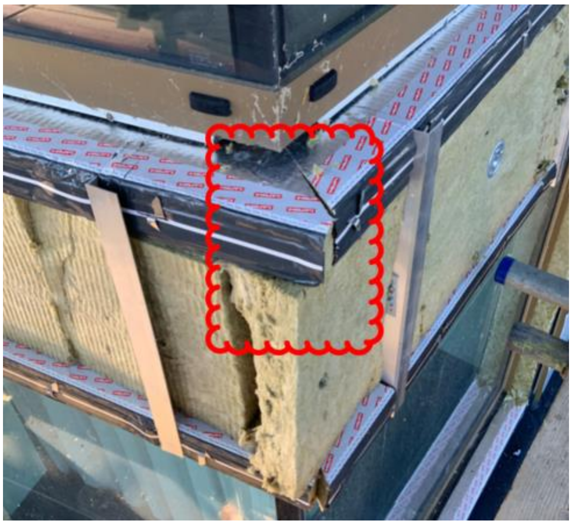


Figure 13 - Absence of intumescent strips at the corners highlighted in red cloud.

4 Open State Cavity Barrier

The OSCB for external walls stands as a sophisticated and integral component within contemporary building systems, strategically designed to enhance fire safety and mitigate the spread of fire in exterior wall cavities. Positioned within concealed spaces or cavities of external walls, this barrier operates on the principle of compartmentalization, serving as a critical safeguard against the unhindered progression of fire throughout different sections of a building. When a fire initiates, the OSCB promptly activates, expanding to fill the wall cavity and effectively sealing potential pathways for the vertical or horizontal travel of fire, smoke, and heat [27]. This proactive measure restricts the fire's capacity to escalate within the structure, playing a pivotal role in containing flames and minimizing potential damage. Beyond preserving the building's structural integrity, this barrier gives invaluable time for occupants to evacuate and enables firefighters to respond effectively, making it an indispensable element in ensuring the safety of both the structure and its occupants during a fire emergency [16].

The OSCB are generally made up of compressed stone wool lamella strips and has a foil facing. The front facing part of the cavity barrier will be provided with an intumescent strip which will expand and close the cavity during a fire incident. The product will be supported with foil taps rated for a 120 minutes integrity and 45 minutes insulation and steel mechanical fixings for the installation purpose. The installation of OSCB is always in horizontal around the openings over the wall and also at the compartmentation levels as indicated in the Figure 14. [27]

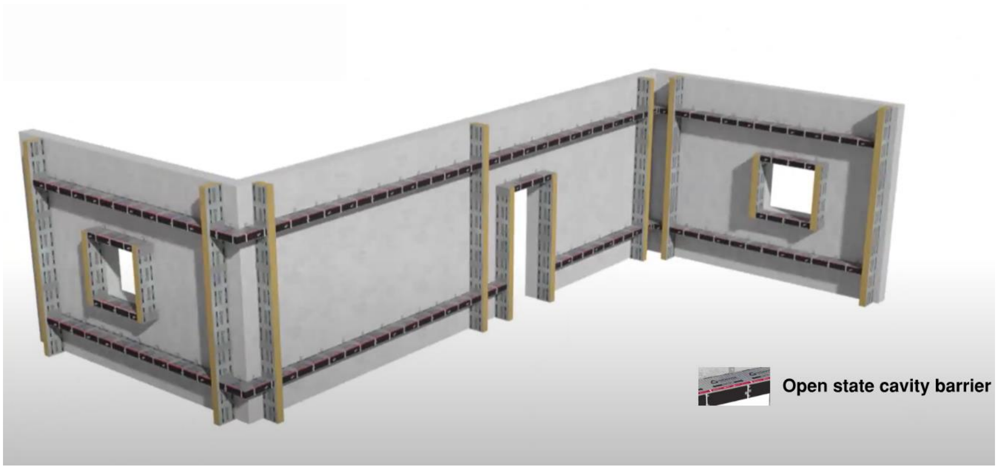


Figure 14 -Open state cavity barrier installing locations for an external wall (Siderise website)

The installation of the OSCB emerges as a crucial step in reinforcing fire safety within the cavities of a building's external walls. Detailed guidelines for installation, in accordance with SIDERISE UK's specifications, are outlined in the accompanying Appendix A.

For the experiment, a product with dimensions of 75x75x1200 mm was used, specifically the product RH/25 – 90/30. Tailored for void ranges spanning from 26 mm to 425 mm, with an air gap of under 25 mm and a tolerance of ±3 mm, these products demonstrate the capability to maintain fire integrity for up to 90 minutes and provide insulation for up to 30 minutes. This information is crucial for understanding the performance characteristics of the OSCB.

5 Experimental Setup and Procedure

As discussed in the section 3.1, the major concerns due to workmanship in installing the cavity barriers were identified. There are total of seven scenarios considered for the experiment and they are:

- Scenario 1: OSCB installed in accordance with manufacturer guidelines;
- Scenario 2: 15 mm gap between two blocks of the OSCB;
- Scenario 3: 30 mm gap between two blocks of the OSCB;
- Scenario 4: 45 mm gap between two blocks of the OSCB;
- Scenario 5: Blockage created by a 50 mm x 25 mm L block in front of the OSCB;
- Scenario 6: 50% more cavity space in front of the intumescent strip of the OSCB;
- Scenario 7: Intumescent strip expansion for the OSCB installed at the corners.

The experimental configuration varies across different scenarios, although a common setup involves the installation of the OSCB over a gypsum board, positioned in front of another gypsum board, as illustrated in Figure 15. K-type thermocouples, each with a thickness of 1 mm, were employed for the experiment, and their specific locations varied according to the distinct scenarios under consideration. Thermocouple readings were systematically measured and recorded using a data logger. The frame of the experimental arrangement was constructed using timber and aluminium framings, secured with steel fixings. A cubic propane sand burner, positioned at the base of the experimental setup as depicted in Figure *15*, was utilized throughout all experiments, featuring a consistent fuel supply rate of 0.4 g/s. Comprehensive documentation of the entire experiment was captured via a Sony-HXR-NX80 video camera. The measurements as taken using the measuring tape and Vernier Calliper. [30]

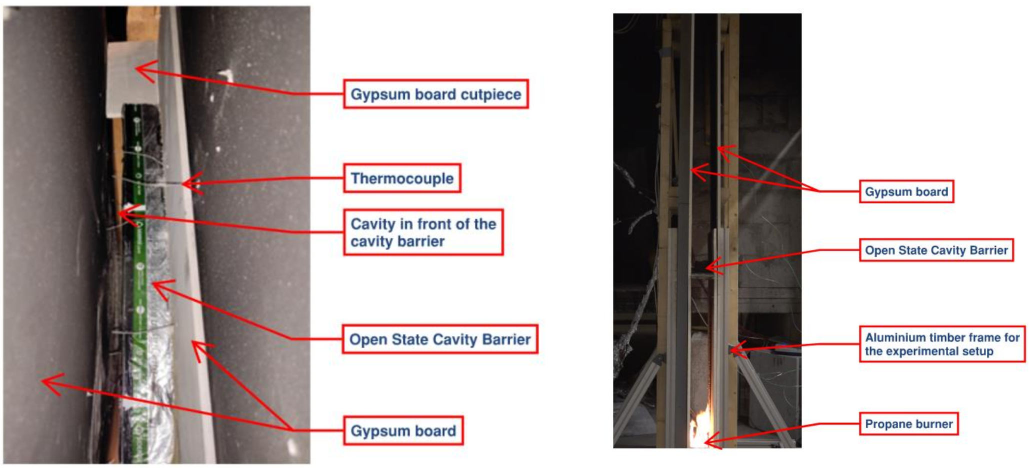


Figure 15 - Open state cavity barrier (a) installed inside the experimental setup top view (b) Experimental setup side view.

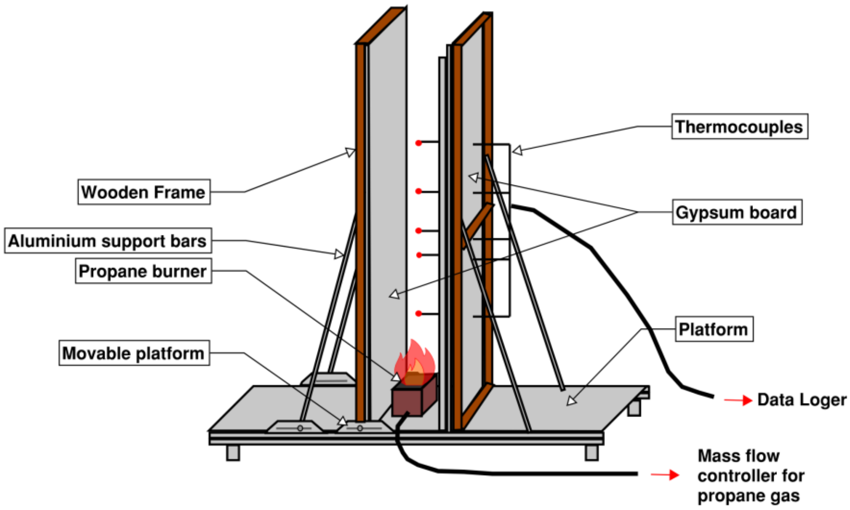


Figure 16 - Experimental setup for the installation of OSCB

5.1 General Procedure

The experimental procedure involves several key steps. Initially, the cavity barrier will be installed within the experimental setup. Subsequently, the propane burner will be ignited and allowed to burn continuously for a duration of 5 minutes. During this time, temperature readings at specific predetermined locations within the setup will be continuously monitored using thermocouples, and the entire experiment will be recorded on video.

Following the conclusion of the 5-minute burning period and once the setup has sufficiently cooled down, the cavity barrier will be carefully removed from the experimental arrangement. This removal will facilitate further analysis, particularly regarding the extent of expansion of the intumescent material and the evaluation of cavity closure.

For all the experiments, both the front view and the top view photographs taken prior to and after the experiments to ascertain the degree of cavity closure. This assessment was facilitated using the Bluebeam Revu x64 Standard software. The method of measurement is by scaling the picture using identified or physically measured values and thereby calculating the area. It is important to highlight that a measurement tolerance of ±10% with respect to the exact value was taken into account during this process to accommodate any potential variations in the measurements.

Should any damage, breakage, or cracks be observed in the gypsum boards used to seal the unoccupied cavity space and those supporting the installation of cavity barrier, will be promptly replaced with new ones. This step is essential to maintain the integrity and consistency of the experimental conditions for subsequent sets of experiments.

5.2 Scenario 1: Open State Cavity Barrier installed as per Manufacturer Guidelines

In this scenario the installation of the OSCB adhered to the manufacturer's guidelines. The outcomes obtained under this specific scenario will serve as the baseline for subsequent comparisons with other scenarios, particularly those incorporating variations in workmanship efficacies.

5.2.1 General statement

The installation of the OSCB was executed meticulously, adhering to the manufacturer's prescribed guidelines. This precise installation was carried out with the explicit purpose of investigating the performance of cavity barriers in the event of a fire. Comprehensive specifications pertaining to the specific cavity barrier utilized in the experiment are outlined in Section 4. The dimensions of the cavity barrier employed for this particular scenario are visually represented in Figure 17. Furthermore, the installation for the cavity barrier within the experimental setup is shown in Figure 18. A cut piece of gypsum board is provided at the ends of cavity barrier in order to prevent the flame going to the cavity above the installed OSCB.

Figure 17 - Dimensions of the cavity barrier used for scenario 1 (a)side view (b)top view (c) front view (d) OSCB after installation

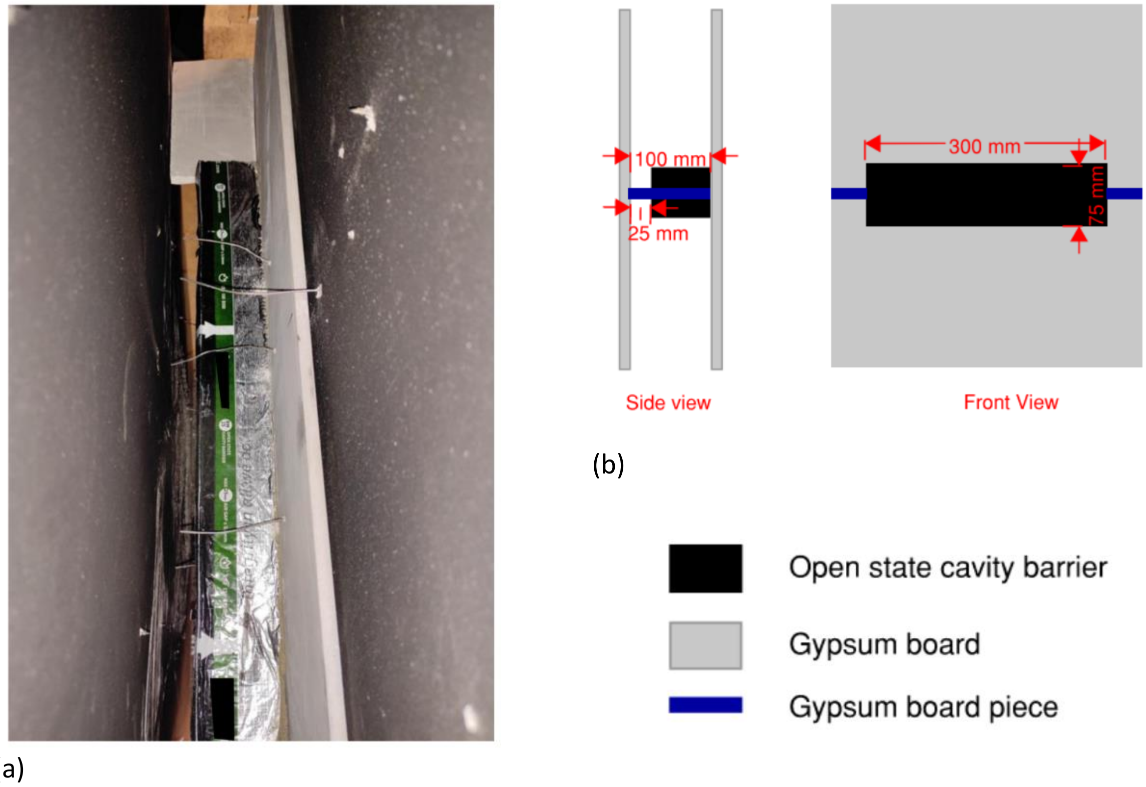


Figure 18 - Cavity barrier installed inside the experimental setup for the scenario 1 (a) installed OSCB (b) section diagram showing the dimensions

5.2.2 Setup

Scenario 1 was conducted in three distinct sets, with the resulting dataset subjected to thorough and extensive analysis. In order to enhance clarity and facilitate a more comprehensible presentation, the entire experimental setup was categorized into two clearly defined zones. "Zone 1" corresponds to the region located beneath the cavity barrier, while "Zone 2" pertains to the area situated above the cavity barrier, as visually depicted in Figure 19. To effectively seal the unoccupied cavity space extending from the edge of the cavity barrier, gypsum boards were strategically employed, as highlighted in blue within Figure 19.

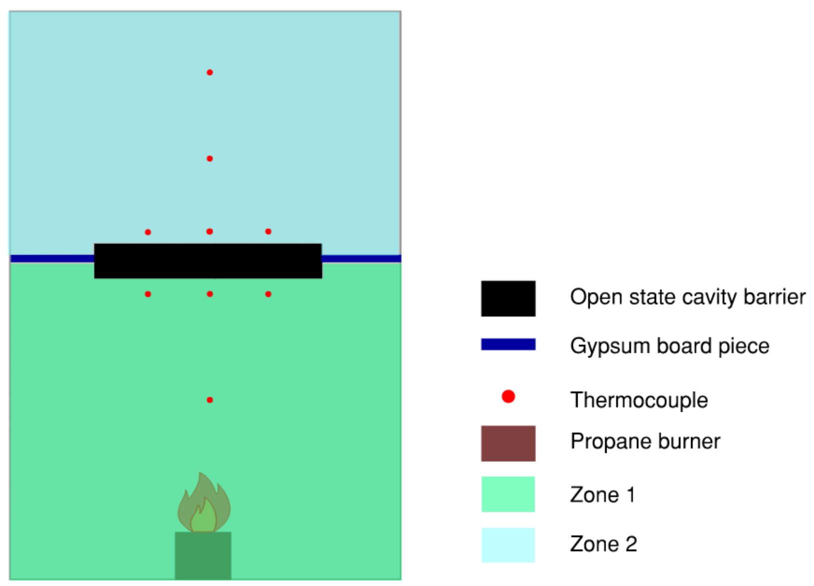


Figure 19 - Two zones of the scenario 1

The experimental setup, as illustrated in Figure 20, included a total of nine strategically positioned thermocouples at various vertical locations. These specific heights were carefully chosen at intervals of 50 cm, 93 cm, 106 cm, 120 cm, and 183 cm, with each measurement originating from the base of the cubic propane burner. These thermocouples were utilized to monitor temperature variations at precise elevations within the experimental arrangement.

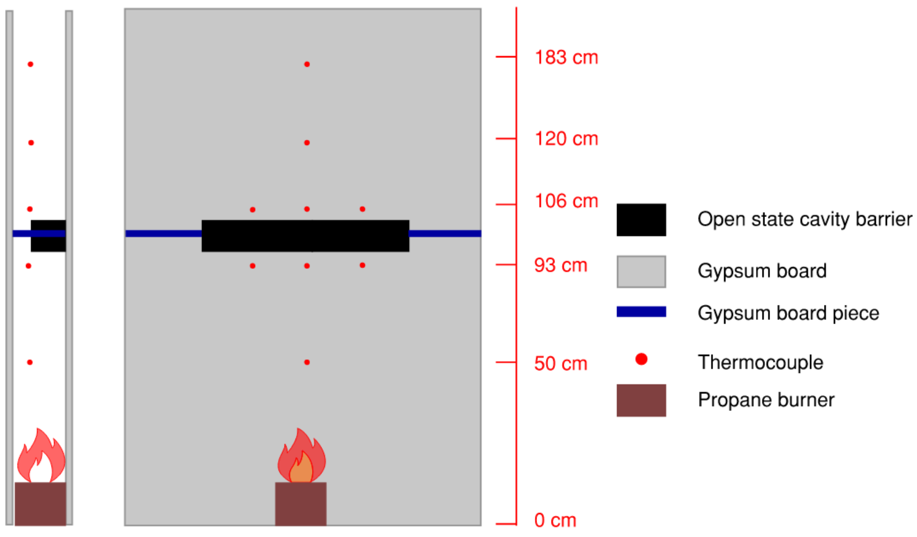


Figure 20 – Section view of experimental setup for the Scenario 1

5.2.3 Area consideration while measuring the expansion of intumescent strip

The measurement of the expanded intumescent strip's area was conducted by a well-defined region, referred to as "Area 1" as visually depicted in Figure 21. The mentioned Area 1 one will be filled with the intumescent strip during a fire incident a prevent the fire and smoke penetration to the upper compartment. Throughout the tests, the force of gravity played a significant role in causing the expanded intumescent material to sag and occupy the cavity, the indicated as "Area 1" is the region were the expansion happened and the sagging of intumescent material happened while expanding. These are further explained with photographic evidence in the section 6.1.1.

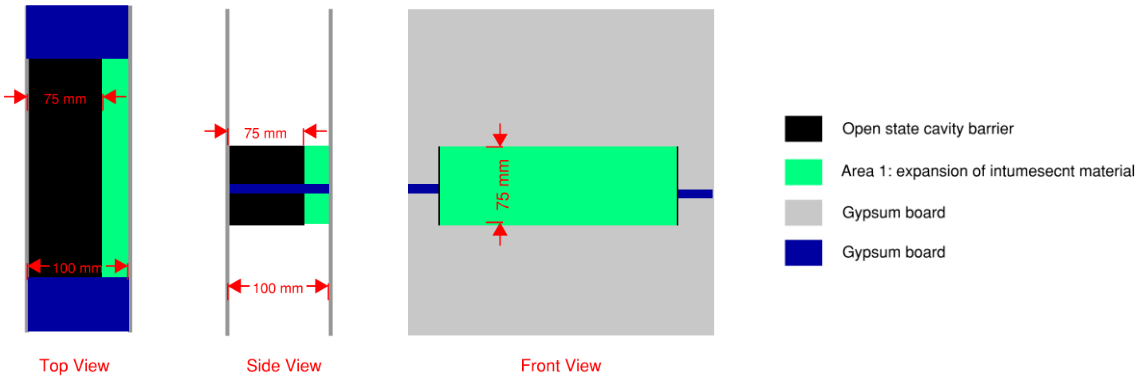


Figure 21 - The area considered for the measurement of intumescent material after the expansion

5.3 Scenario 2, 3 and 4: Gap in between two blocks of the cavity barrier

For these three scenarios, the effectiveness of OSCB is assessed, specifically focusing on situations where there exists a gap between two blocks of cavity barriers. This gap is typically observable at the junctions where two blocks of cavity barriers meet. The results obtained in this scenario will offer insights into the impact of gap size on the potential spread of fire to the upper compartments.

5.3.1 General statement

One of the primary concerns when installing OSCB is the potential presence of gaps between two barrier blocks. These gaps have the potential to hinder the proper closure of the cavity when the intumescent material expands. To investigate the impact of gap size on fire spread, conducted three distinct experiments. These experiments involved gaps measuring 15 mm, 30 mm, and 45 mm between two cavity blocks, as visually represented in Figure 22.

(a) (b) (c)

Figure 22 - Different gaps between two blocks of the cavity (a) 15 mm gap (b) 30 mm gap (c) 45 mm gap

5.3.2 Experimental Setup

The specifications of the cavity barriers used in these experiments align with the details provided in section 5. Each experiment was carried out in three sets, and the resulting data were thoroughly analysed. To simplify comprehension, the entire experimental setup was categorized into two distinct zones. "Zone 1" refers to the area below the cavity barrier, while "Zone 2" pertains to the area above the cavity barrier, as illustrated in Figure 23.

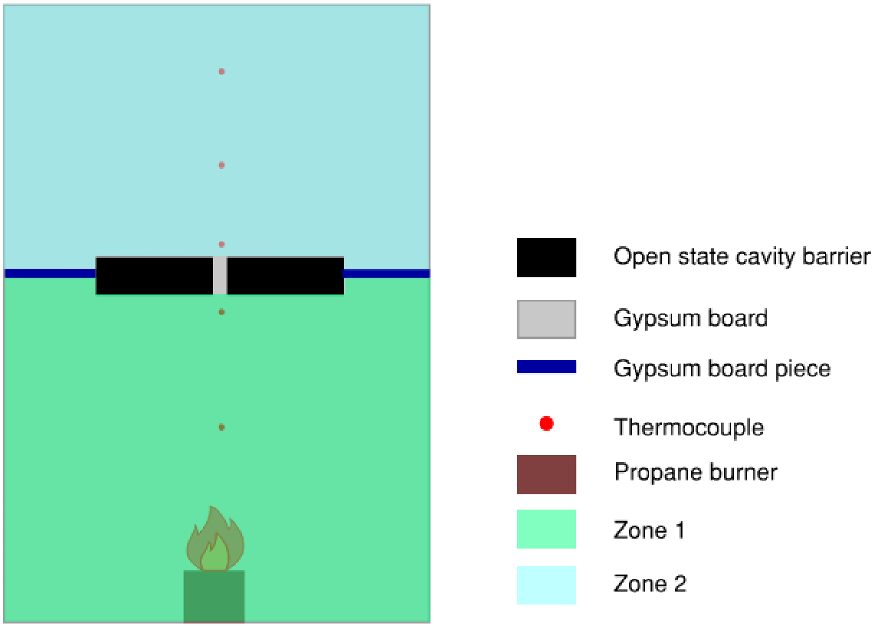


Figure 23 - The two zones of the Scenario 2, 3 and 4

Figure 24 –The OSCB blocks installed within the experimental setup with a gap in between.

The experimental setup, as illustrated in Figure 25, included five thermocouples strategically positioned at different heights to monitor temperature variations at specific elevations. These heights were precisely set at 50 cm, 93 cm, 106 cm, 120 cm, and 183 cm measured from the base of the cubic propane burner.

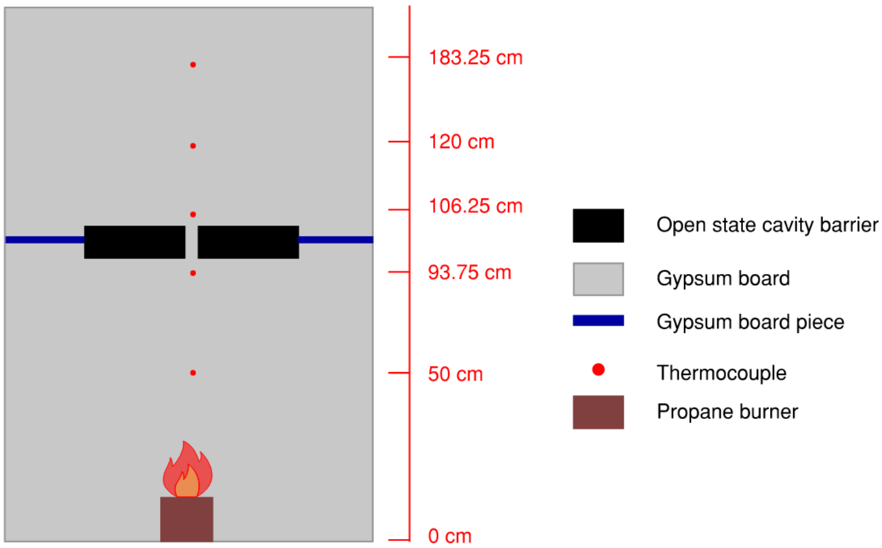


Figure 25 –Front view section of the experimental setup for Scenario 2, 3 and 4.

5.3.3 Area consideration while measuring the expansion of intumescent strip

The measurement of the intumescent strip expansion area was conducted by dividing it into two distinct regions, referred to as "Area 1" and "Area 2," as visualized in Figure 26. During the tests, the gravitational force played a significant role in causing the expanded intumescent material to sag and occupy the cavity, primarily within the confines of "Area 2."

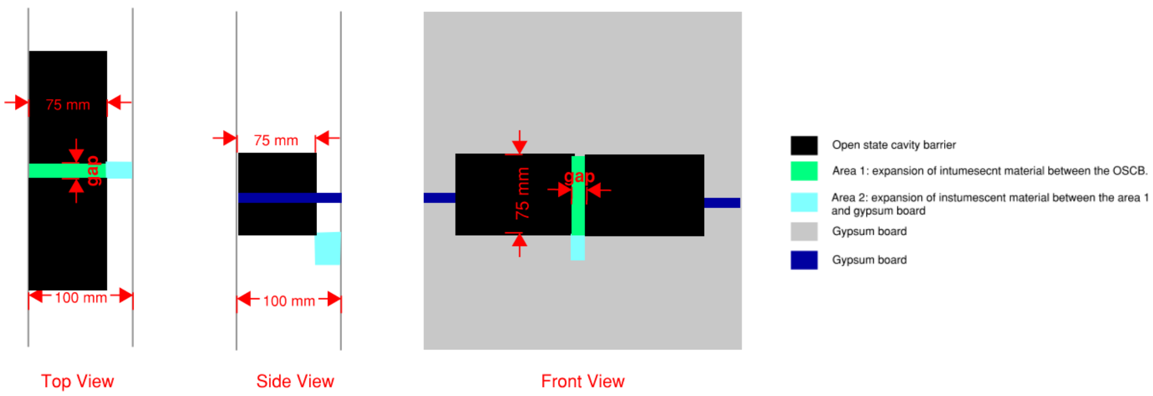


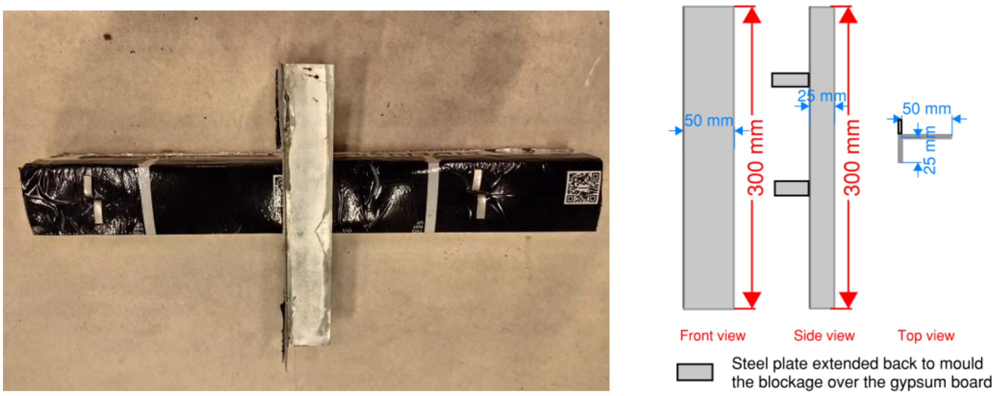
Figure 26 - Area considered for the measurement of intumescent material after expansion

5.4 Scenario-5: Cavity barrier installed with blockage in front of intumescent material

In this scenario, the effectiveness of OSCB is assessed, specifically focusing on situations where blockages in front of the cavity barriers are present. These blockages are typically observable at the locations where the cladding rails are installed in front of the cavity barriers without following proper installation methods. This encompasses situations where metal panel rain screen claddings are installed with a workmanship issue, characterized by the omission of the open-state cassette insert, as delineated in Section 3.1.

5.4.1 General statement

One of the significant concerns during the installation of OSCB is the possibility of encountering blockages in front of the cavity barrier. These blockages have the potential to impede the proper expansion of the intumescent material. In order to investigate the impact of gap size on the spread of fire, a series of experiments were conducted. These experiments involved the installation of an L-shaped steel angle, as illustrated in Figure 27(b), positioned in front of the cavity barrier. The specific dimensions and installation details of the angle were in accordance with those depicted in Figure 27(a). This size of L angle is commonly utilized within the construction industry for the installation of cladding in front of cavity barriers.



(a) (b)

Figure 27 – Installation of cavity barrier with L angle. (a) Experimental setup front view (b) Section drawing for the L steel angle

5.4.2 Experimental Setup

The experiments were conducted across three separate sets, and the resulting data underwent a comprehensive analysis. To enhance clarity and facilitate understanding, the entire experimental setup was divided into two clearly defined zones. "Zone 1" corresponds to the area situated beneath the cavity barrier, while "Zone 2" pertains to the area located above the cavity barrier, as visually depicted in Figure 28.

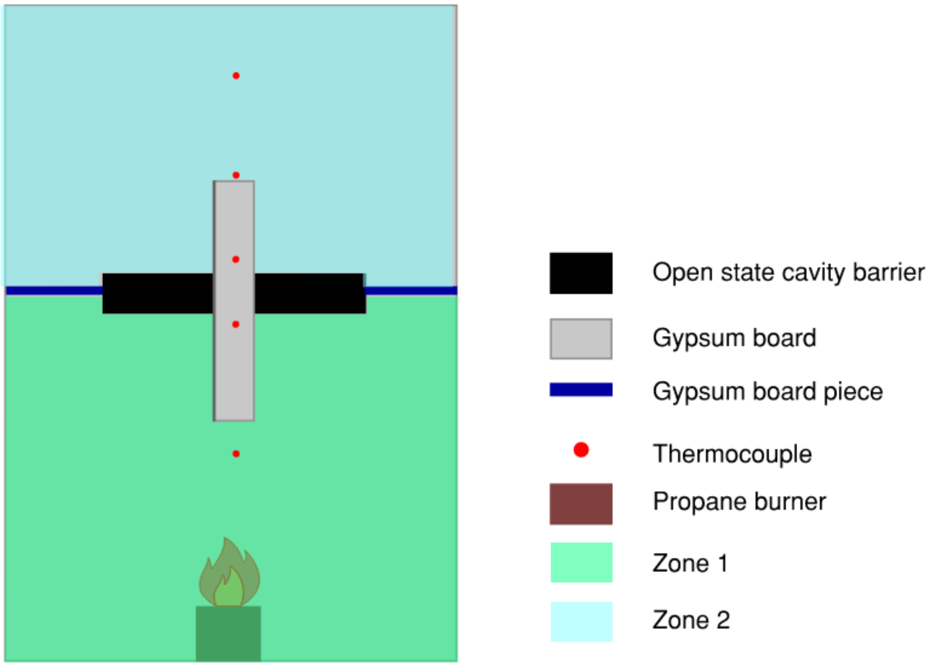


Figure 28 - The two zones considered for the Scenario 5

Figure 29 – The cavity barrier installed with an L steel angle in front.

The experimental arrangement, depicted in Figure 30, featured five strategically placed thermocouples at varying vertical positions. These specific heights were accurately established at intervals of 50 cm, 93 cm, 106 cm, 120 cm, and 183 cm, each measured from the base of the cubic propane burner. These thermocouples were employed to monitor temperature fluctuations at precise elevations within the experimental setup.

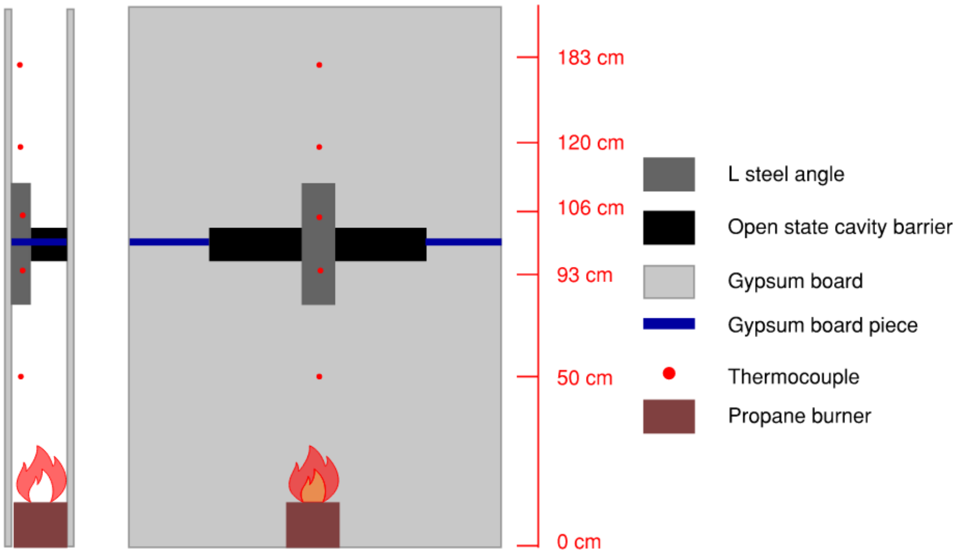


Figure 30 – Section views (Side and front) showing typical experimental setup for Scenario 5.

5.4.3 Area consideration while measuring the expansion of intumescent strip

The measurement of the expanded intumescent strip's area was carried out by dividing it into the distinct region, specifically denoted as "Area 1," as visualized in Figure 31. Throughout the course of the tests, the influence of gravitational force played a significant role in causing the expanded intumescent material to sag and occupy the cavity, primarily within the boundaries of "Area 1."

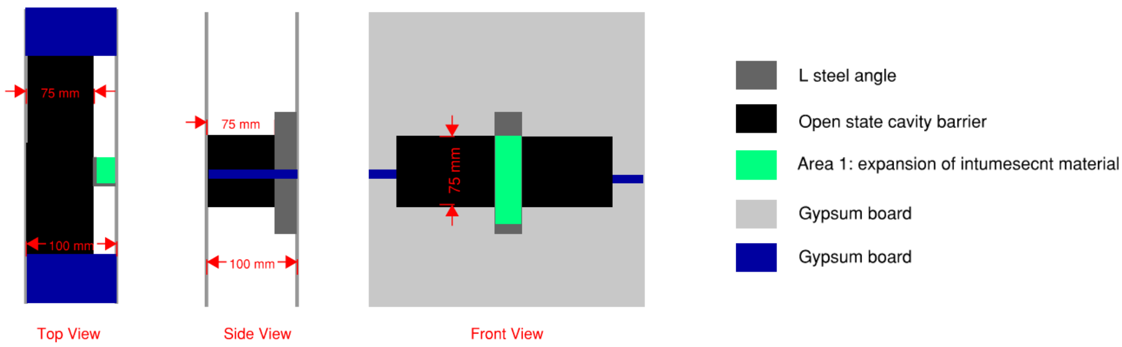


Figure 31 - The area considered for the measurement of intumescent material after expansion

5.5 Scenario-6: Open State Cavity Barrier installed with a 50% wider gap.

In this specific scenario, the evaluation of OSCB is considered where the cavity in front of the barrier surpasses the threshold where the product can achieve optimal closure. This extended cavity is frequently observed on construction sites, often attributed to challenges in accurately maintaining the gap between the sheathing boards and the rainscreen cladding. The outcomes derived from this scenario will provide valuable insights into how the extended cavity influences the propagation of flames and smoke to the upper compartment.

5.5.1 General statement regarding the Scenario 6

One of the key concerns during the installation of OSCB is the possibility of encountering a larger cavity in front of the cavity barrier. These enlarged gaps have the potential to impede the proper closure of the cavity through the expansion of the intumescent material during a fire event. In order to investigate the impact of gap size on the spread of fire, a series of tests were conducted.

These tests involved the installation of a cavity barrier designed for the closure of a 25 mm gap through the expansion of the intumescent strip. However, for experimental purposes, the gap size was deliberately increased to 38 mm, which represents a 50% increase over the manufacturer's guideline, as depicted in Figure 32(a) and Figure 32(b). These tests aimed to assess how this larger gap would affect the performance of the cavity barrier in preventing fire spread.

(a) (b)

Figure 32 - installation of cavity barrier inside the experimental setup for scenario 6 (a) Side view (b) Front view

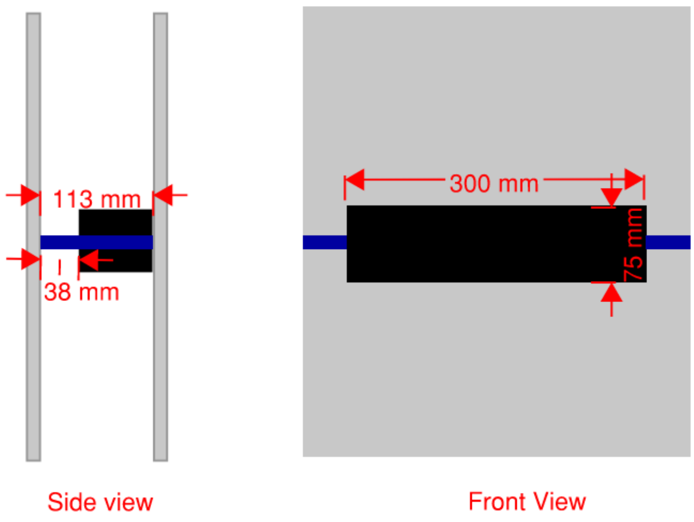


Figure 33 - The cavity barrier installation with dimensions for the scenario 6

5.5.2 Experimental Setup

The experiments were conducted across three distinct sets, and the resultant data underwent a comprehensive analysis. To enhance clarity and facilitate understanding, the entire experimental setup was divided into two well-defined zones. "Zone 1" represented the region located beneath the cavity barrier, while "Zone 2" corresponded to the area situated above the cavity barrier, as visually depicted in Figure 34.

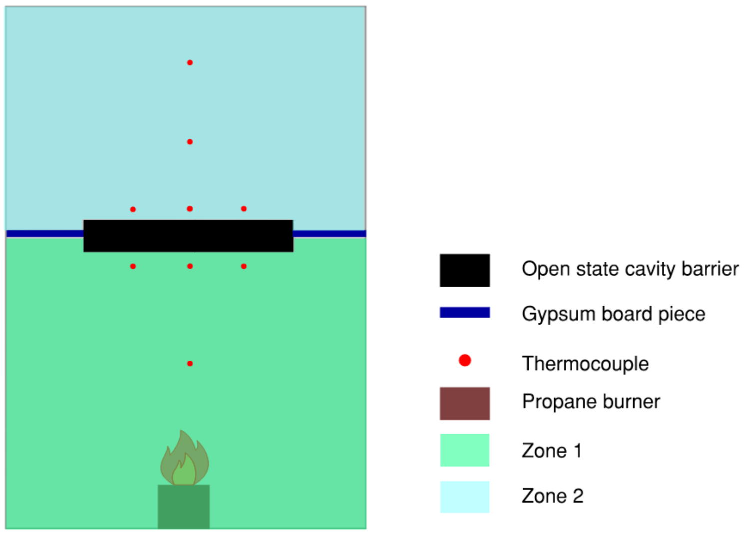


Figure 34 - The two zones of the Scenario 6

Figure 35 –The cavity barrier blocks installed for the scenario 6.

The experimental configuration, as depicted in Figure 36, featured nine strategically placed thermocouples at varying heights. These thermocouples were located at 50 cm, 93 cm, 106 cm, 120 cm, and 183 cm, each measured from the base of the cubic propane burner. These thermocouples were strategically positioned to monitor temperature fluctuations at precise elevations within the experimental setup.

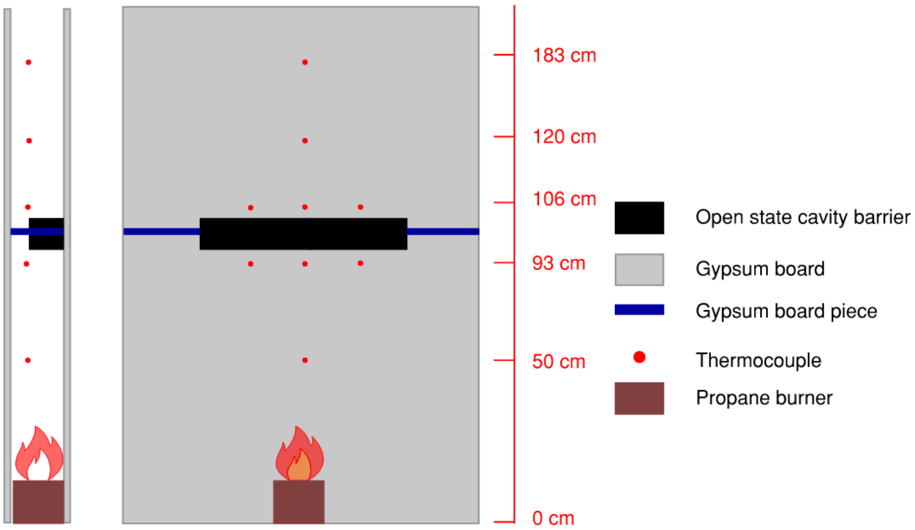


Figure 36 –Side view and front view of the experimental setup for Scenario 6.

5.5.3 Area consideration while measuring the expansion of intumescent strip

The measurement of the intumescent strip expansion area was conducted by partitioning it into the distinct region, specifically referred to as "Area 1," as depicted in Figure 37. It's worth noting that the focus of this measurement was on quantifying the area of unexpanded intumescent material over the cavity barrier, with the area of the expanded portion excluded from consideration.

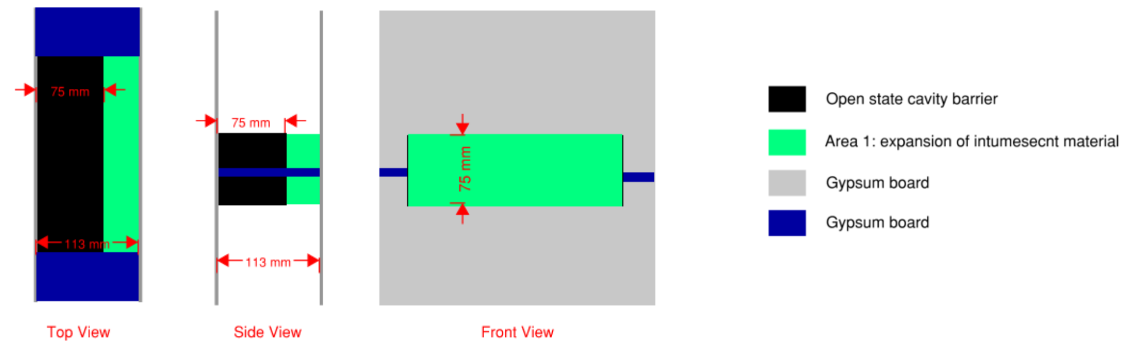


Figure 37 - Area considered for the measurement of intumescent material after expansion for Scenario 6

5.6 Scenario-7: Cavity barriers at corners

In this particular scenario, the assessment of OSCB focuses on their efficacy at corners. The challenge arises from the fact that, typically, installations at corners may not adhere strictly to the manufacturer's guidelines. Even when following guidelines, there is a possibility that, during the cutting process for joining cavity barriers at corners, the intumescent part may be removed. This omission has the potential to diminish the quality of cavity closure at corners. The outcomes obtained from this scenario will yield crucial insights into how the extended cavity closure at corners influences the spread of flames and smoke to the upper compartment.

5.6.1 General statement

One of the concerns during the installation of OSCB relates to the proper expansion of intumescent material, particularly at the corners. Typically, the cavity barrier is configured by following specific cutting and joining methods, as depicted in Figure 38. To address this concern and assess the behaviour of cavity barriers in corner fire scenarios, a specially constructed corner-shaped sheet metal piece was used, as shown in Figure 39.

5.6.2 Experimental Setup

In this experiment, a gap of 25 mm was maintained between the sheet metal and the intumescent strip of the cavity barrier to replicate real-world conditions and better understand how cavity barriers perform in corner fire situations. The detailed installation of cavity barriers is explained in the section 4.

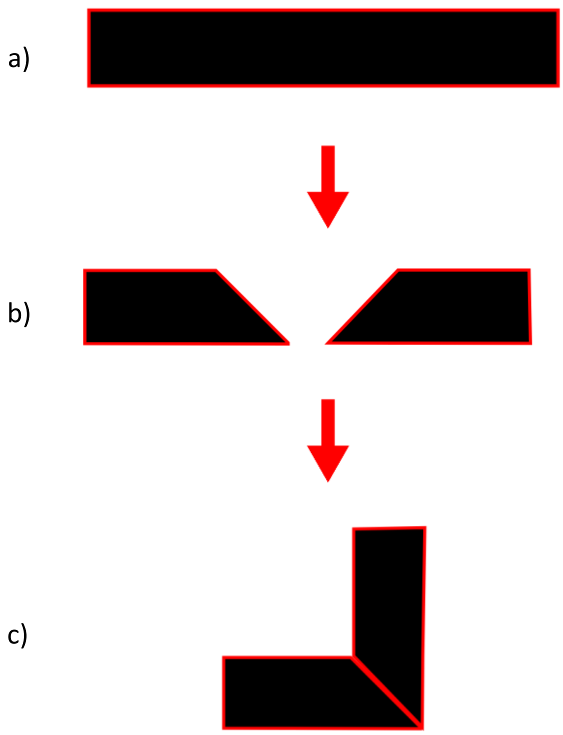


Figure 38 – The installation of cavity barriers at corners align with the manufacturer's guidelines.

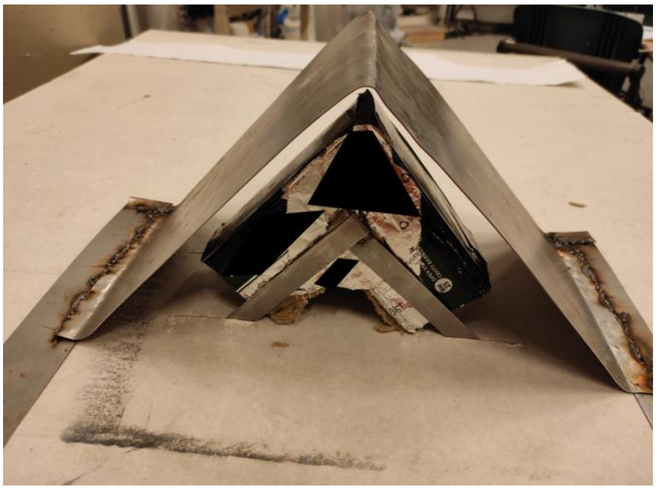


Figure 39 - The installation of cavity barrier for the scenario 7

The experiments were organized into three sets, and the resulting data were subjected to a comprehensive analysis. To enhance clarity and facilitate understanding, the entire experimental arrangement was divided into two distinct zones: "Zone 1" representing the area situated below the cavity barrier, and "Zone 2" denoting the area positioned above the cavity barrier. This division is visually depicted in Figure 40. The installed cavity barrier in the experimental setup is indicated in the Figure 41.

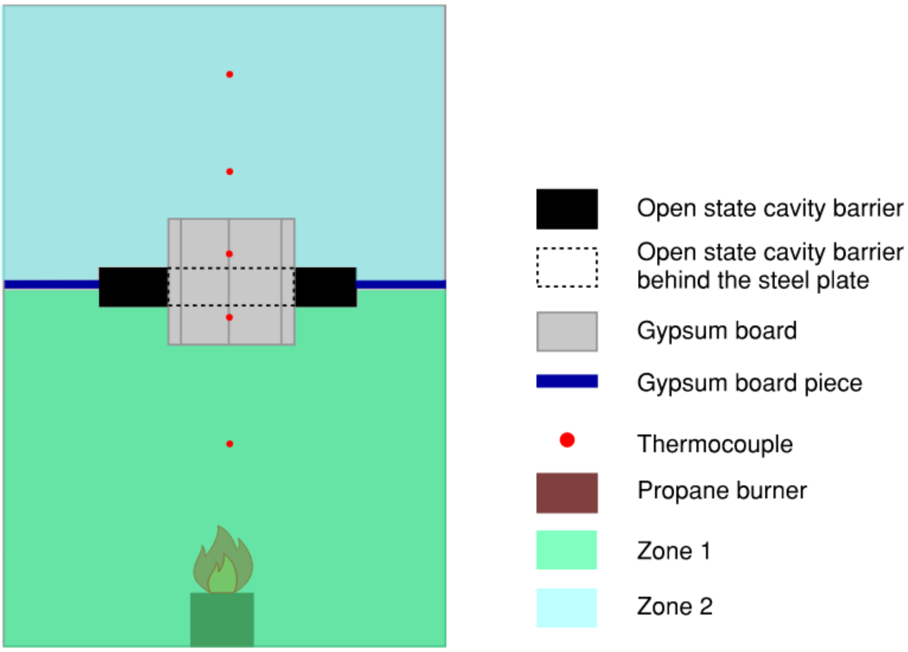


Figure 40 - The two zones of the experiment

Figure 41 –The installed cavity barrier for the scenario 7.

The experimental setup, depicted in Figure 42, incorporated the placement of five thermocouples at strategic locations and different heights. These thermocouples were utilized to monitor temperature fluctuations at specific elevations within the experimental arrangement. The heights at which these thermocouples were positioned were meticulously determined and set at intervals of 50 cm, 93 cm, 106 cm, 120 cm, and 183 cm, all measured from the base of the cubic propane burner.

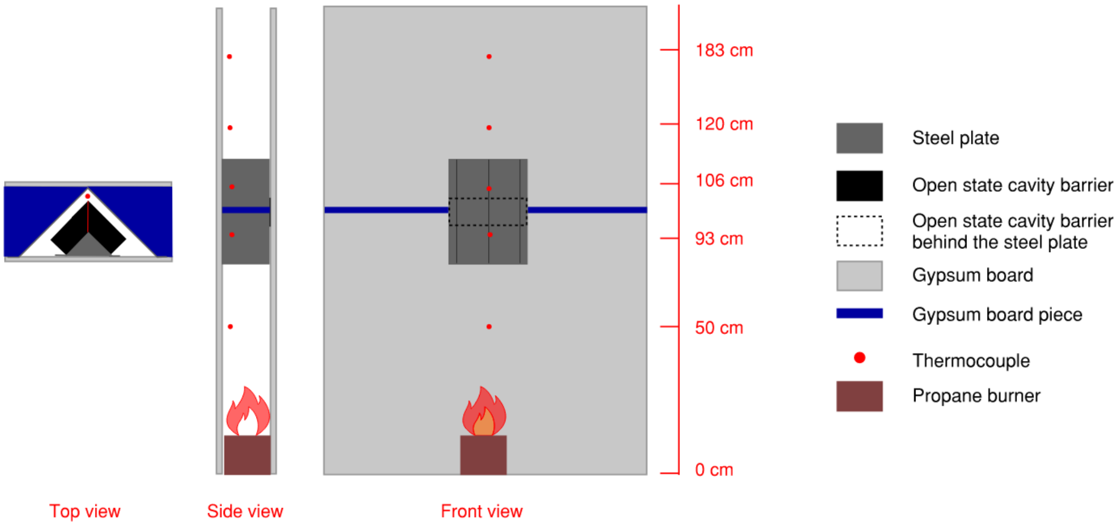


Figure 42 –Front view of the experimental setup for scenario 7.

5.6.3 Area consideration while measuring the expansion of intumescent strip

The measurement of the area of intumescent strip expansion was carried out by dividing it into the specific region, designated as "Area 1," as depicted in Figure 43. During the experimental tests, the influence of gravitational force played a significant role in causing the expanded intumescent material to sag and occupy the cavity, predominantly within the boundaries of "Area 1."

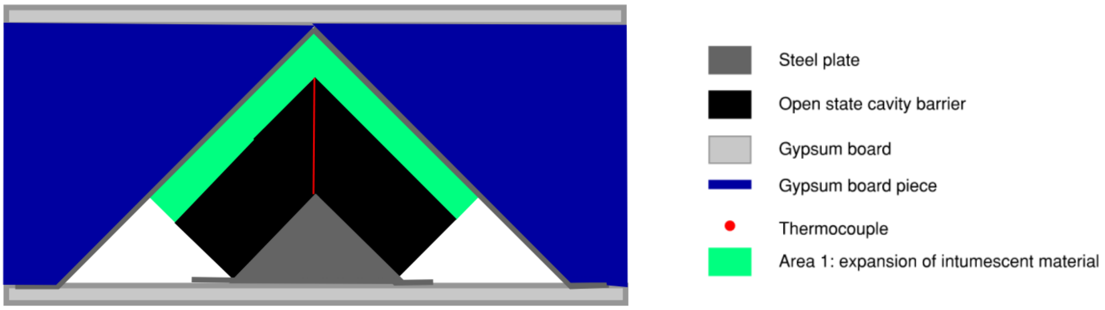


Figure 43 - Area considered for the measurement of intumescent material after expansion

6 Results

The implementation of cavity barriers aligned with each specified scenario was meticulously carried out, and subsequent experiments were systematically conducted. Key datasets employed for the comprehensive analysis of the experiments encompassed thermocouple readings, video footage capturing the test, and conclusive measurements obtained for the expanded intumescent material over the OSCB. These datasets form the core of the analytical framework, providing essential information for a thorough examination of the outcomes derived from each scenario.

6.1 Scenario 1: Installation of cavity barriers as per Manufacturer Guidelines

Scenario 1 was designed with the primary objective of evaluating the effectiveness of cavity barriers when installed in strict adherence to the manufacturer's stipulated guidelines. The installation procedures strictly followed the specifications outlined in Section 5.2.1. Following the installation, an experimental assessment was carried out spanning a duration of five minutes, with the timer commencing at the point of ignition of propane gas within the cubical burner. The data employed for subsequent analysis encompassed a range of information, including readings from thermocouples, photographic documentation, and measurements acquired for the expanded intumescent strip.

6.1.1 Observations and Temperature measurements

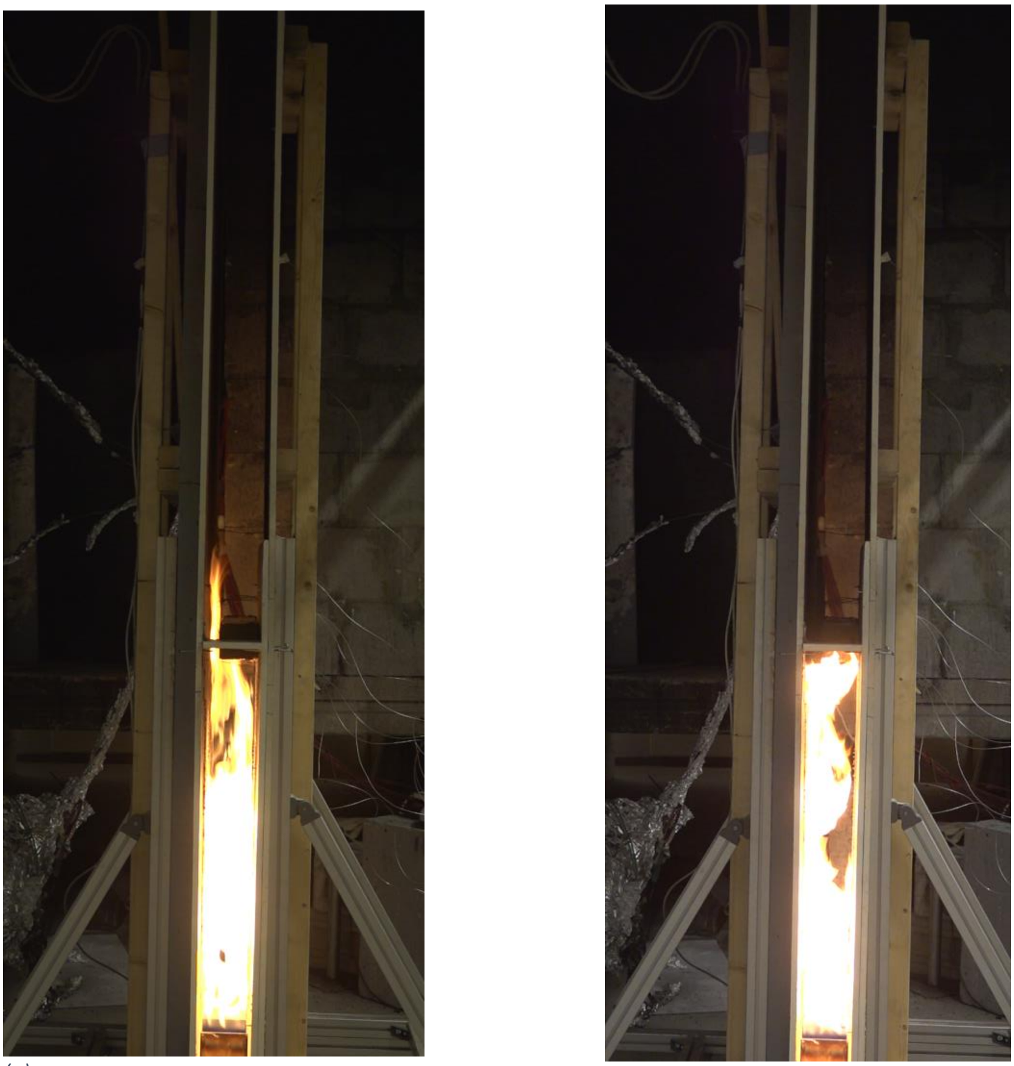
The evaluation of intumescent strip expansion involves distinct zones as outlined in Section 5.2.2. These designated regions, referred to as "Area 1" are individually appraised to measure the degree of closure attained in the event of a fire. To facilitate a visual representation of this evaluation, refer to Figure 44, which provide photographic documentation depicting the condition of the cavity barrier both prior to and following exposure to a fire for 5 minutes.

(a) (b)

Figure 44 - Before and after images for expansion of the intumescent strip (a) before (b) after

The video recordings of the experiment provide insight into the sequence of events. Specifically, between the 17th and 20th seconds after the ignition of the propane burner, the expansion of the intumescent strip occurred, leading to the effective closure of the cavity. Subsequently, no discernible flames were observed in Zone 2 penetrating through "Area 1" following the intumescent strip's expansion.

During the initial stages of ignition, flames were visibly present within the "Area 1," as illustrated in Figure 45(a). However, Figure 45(b) serves as compelling evidence of the complete closure of the cavity, as no flames were observed spreading into Zone 2 at that point.



(a) *(b)*

Figure 45 - Showing the before and after expansion of the intumescent material (a)before at 17th second (b) after at 56th second

Temperature measurements were systematically conducted at various points within both Zone 1 and Zone 2 using thermocouples, in accordance with the procedures outlined in Section 5.2.2. Specifically, the temperature readings were focused on the region just beneath the cavity barrier and were maintained within the narrow band of 400 °C to 500 °C. This temperature range was continually monitored by a thermocouple positioned at a height of 93 cm from the base of the propane burner, while maintaining a controlled propane gas supply rate of 0.4 g/s.

The positioning of the thermocouples within the experimental setup and their significance in determining the cavity closure time due to intumescent strip expansion are detailed in Section 5.2.2. The temperature drop observed for the thermocouple located just above the cavity barrier (at a height of 106 mm from the bottom of the burner), in compliance with the guidelines from TGD 19 [29], was considered as compelling evidence to demonstrate the closure time of the cavity as a consequence of intumescent strip expansion.

Analysis of the temperature data revealed a notable reduction in temperature within Zone 2 after a duration of 20 seconds. The point at which this decrease in temperature was observed for the thermocouple situated just above the cavity barrier, positioned at a height of 106 cm from the bottom of the propane burner, was identified as the precise moment at which "Area 1" achieved complete cavity closure due to the expansion of the intumescent material. In Figure 46, this temperature drop for the aforementioned thermocouple is denoted by a green dotted line.

Furthermore, two additional thermocouples located within Zone 2 consistently registered peak temperatures below 180 °C, never exceeding the critical threshold of 200 °C as guide lined in TGD 19 [29]. Additionally, the thermocouple positioned at the 106 cm mark exhibited a decrease in temperature to 200 °C following the expansion of the intumescent material. Lastly, the thermocouple situated at the highest point of the experimental setup, positioned 183 cm above the base of the propane burner, consistently reported temperatures below 100 °C.

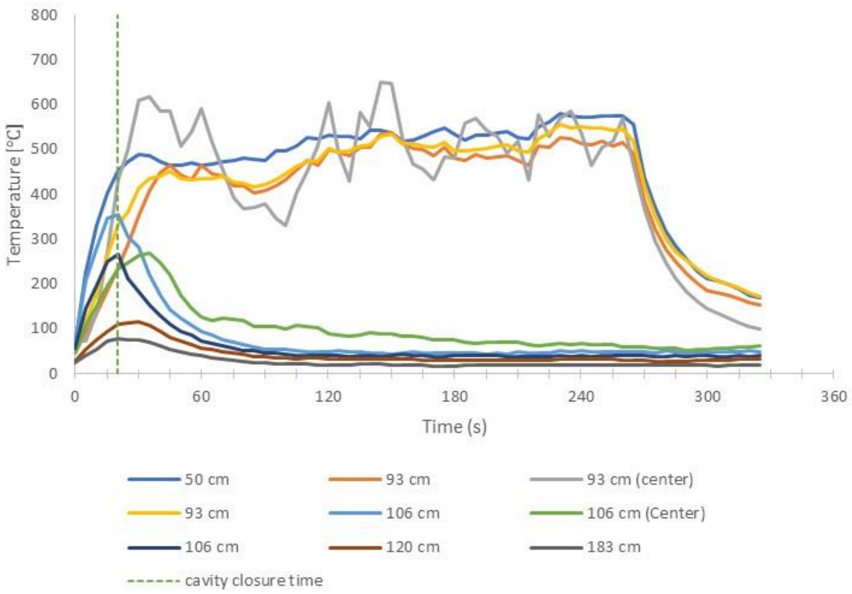


Figure 46 - Thermocouple reading for the scenario 1

6.1.2 Intumescent Material expansion measure

The quantification of the cavity closure area was executed by means of post-experiment photographs, utilizing the Bluebeam Revu x64 Standard software. The area measurement for the frontal perspective was conducted as depicted in Figure 47. Upon examination of the frontal view, the analysis disclosed that, within "Area 1," the unexpanded portion of the intumescent strip over the cavity barrier comprised a range between 23% and 27%. This finding indicates that the expanded intumescent material effectively obstructed the ingress of flames into Zone 2 through "Area 1" even prior to the complete utilization of the entire intumescent material covering the cavity barrier situated above the experimental setup.

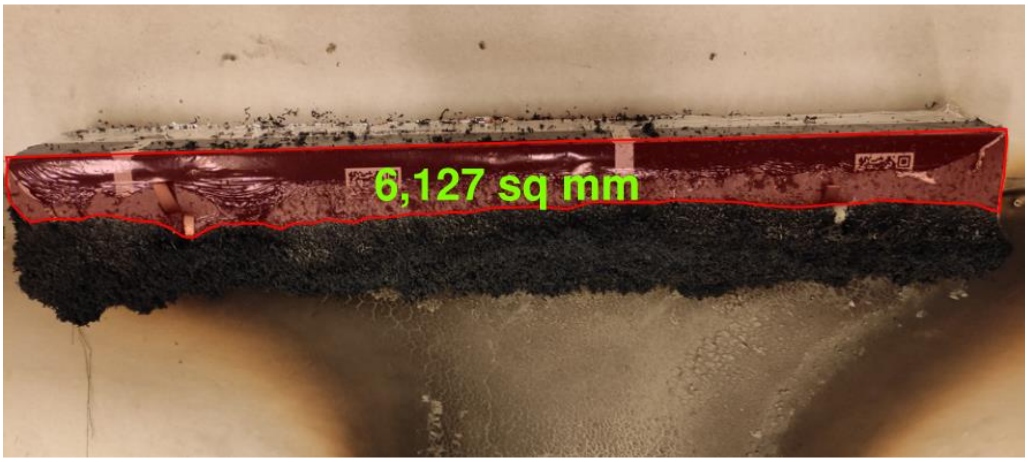


Figure 47 - Front view area measurement for the unexpanded cavity barrier

The unexpanded intumescent material area remained in its unexpanded state due to the temperature drop that occurred in Zone 2 following the closure of the cavity. This correlation became evident when comparing the timing of the temperature drop, as indicated in the graph in Figure 46, with the visual evidence captured in the video footage.

6.1.3 Data's from the three set of tests for the Scenario-1

The dataset for Scenario-1, encompassing results from the three conducted tests, is presented in the Section 6.8 provided. This dataset includes thermocouple readings, measurements of the remaining expanded the intumescent strip, and the percentage of intumescent material that remained unexpanded due to the temperature drop following the closure of the cavity, specifically within "Area 1."

6.2 Scenario-2: 15 mm gap between two cavity barriers.

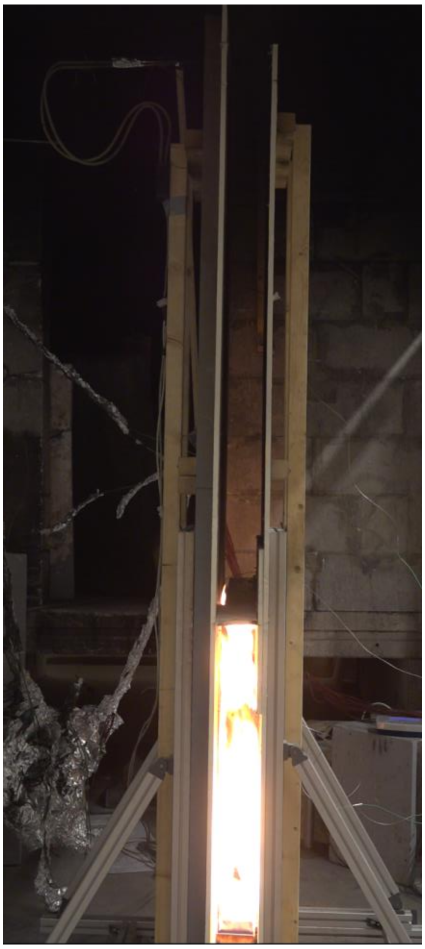
Scenario 2 was with a gap of 15 mm in between the cavity barrier blocks as indicated in Figure 22(a). The test was conducted for five minutes and the timer started from the point of ignition of propane gas at the cubical burner. The data considered for the analysis were of the thermocouple reading, photographs, and measurements taken for the expanded intumescent strip.

The experimental setup showing the location of thermocouples are discussed in the Section 5.3.1 The temperature drops for the thermocouple, placed just above the cavity barrier (at 106 mm height from bottom of the burner) as per the guidance from TGD 19 [29], was considered as an evidence to show the closure time of the cavity due to the expansion of intumescent strip. This point is highlighted in green dotted line in the graphs.

6.2.1 Observation and Temperature measurements

The experiment's video footage reveals that between the 17th and 20th seconds after igniting the propane burner, the intumescent strip expansion was completed, partially closing the cavity. Subsequently, there was no visible flame in Zone 2 through "Area 2" after the intumescent strip expansion. However, a smoke layer was observable in Zone 2 through "Area 1," with smaller and intermittent flames.

During the initial ignition stages until the 20th second, flames were evident through both "Area 1" and "Area 2." Gradually, as approached the 30 second mark, flame visibility in Zone 2 decreased, as depicted in Figure 48(a). Beyond 30 seconds, smoke, accompanied by small flames, emerged through "Area 1," as illustrated in Figure 48(b).


(a)


(b)

Figure 48 - Before and after images of cavity closure due to the expansion of cavity barrier (a) before closure at 16th second (b) After closure at 45th minute

Temperature measurements were conducted at various locations within Zone 1 and Zone 2 using thermocouples, as outlined in Section 5.3.1. Specifically, the temperature just below the cavity barrier was maintained within the range of 400 °C to 500 °C and was continuously monitored by a thermocouple positioned at a height of 93 cm from the base of the propane burner, with a controlled propane gas supply of 0.4 g/s.

The temperature data indicates that after a duration of 30 seconds, there was a noticeable decline in temperature within Zone 2. The moment at which the temperature drop was observed for the thermocouple positioned just above the cavity barrier (at a height of 106 cm from the bottom of the propane burner) was identified as the point at which "Area 2" achieved complete cavity closure due to the expansion of the intumescent material. This temperature drop for the aforementioned thermocouple is highlighted in the graph using a green dotted line as indicated in the Figure 49.

Furthermore, the two other thermocouples situated within Zone 2 recorded peak temperatures below 180 °C, never surpassing the threshold of 200 °C. Additionally, the thermocouple positioned at a height of 106 cm exhibited a decrease in temperature to 200 °C following the expansion of the intumescent material. Lastly, the thermocouple at the highest point of the experimental setup, located 183 cm above the base of the propane burner, did not register temperatures exceeding 100 °C.

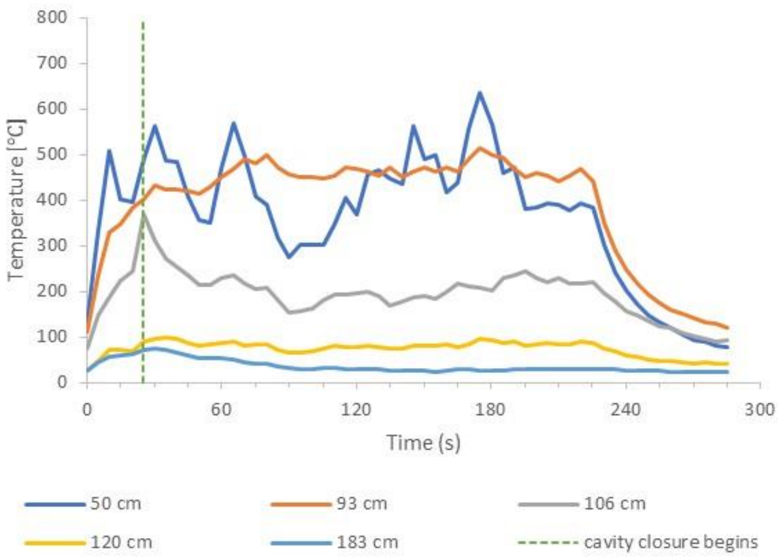
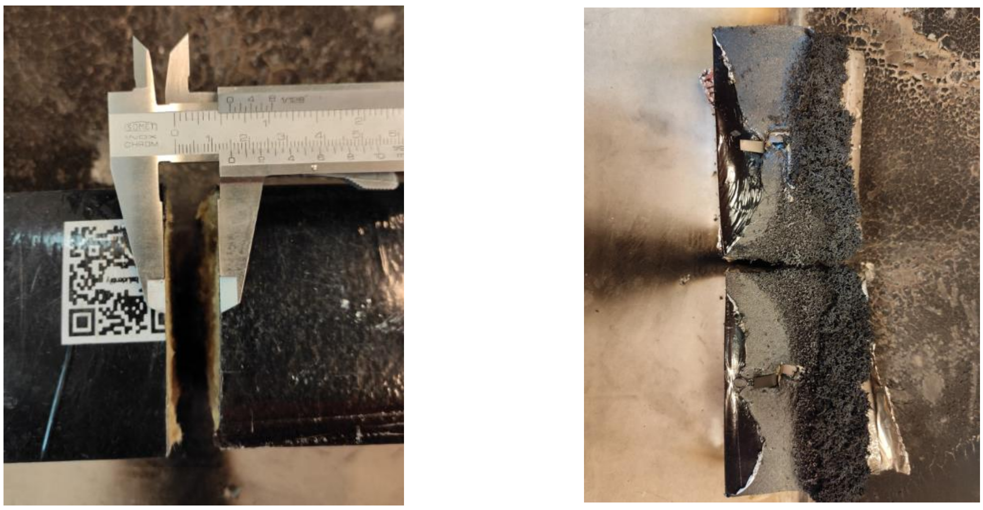


Figure 49 - Thermocouple reading for the experiment with 15 mm gap between the cavity barriers

6.2.2 Expansion area measurement for the Scenario 2

The assessment of intumescent strip expansion encompasses specific regions, as elaborated in Section 5.3.1. These designated areas, denoted as "Area 1" and "Area 2" within this section are assessed independently to quantify the extent of closure achieved during a fire event. To visualize this assessment, reference can be made to Figure 50, where photographic documentation of the cavity barrier's condition before and after the fire.



(a) (b)

Figure 50 - Before and after images of the cavity barrier (a) before burning (b) after burning

The quantification of cavity closure area was conducted using post-experiment photographs, facilitated by the Bluebeam Revu x64 Standard software. Figure 51 and Figure 52 illustrate the measurement of “Area 1” and “Area 2.” The red-coloured area represents “Area 1”, while the blue-coloured area represents “Area 2”. From the frontal perspective, the analysis revealed that for "Area 1," the proportion of unclosed cavity ranged from 48% to 58% after the intumescent strip expansion. Meanwhile, in the case of "Area 2," it was observed that the uncovered cavity ranged from 40% to 52%.

When viewed from the top perspective, the assessment of cavity closure in "Area 1" indicated a range of 85% to 90%. In contrast, for "Area 2," the closure percentage ranged from 12% to 17%. It is noteworthy that during test 2, while the front view suggested a cavity closure of 96% for "Area 2," the top view measurements showed a minimal 0.32% opening. This observation suggests that the expanded intumescent material effectively prevented the intrusion of flames into zone 2 through "Area 2" in the experimental setup.

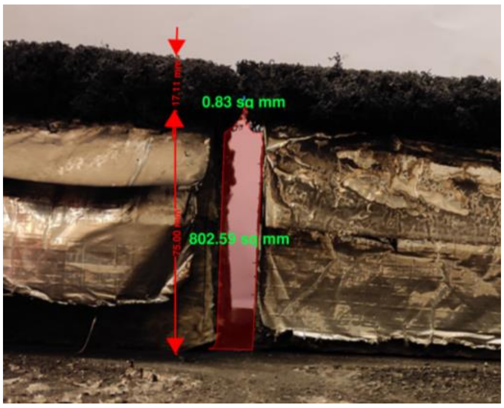


Figure 51 - Area 1 and area 2 of cavity that was not closed after the experiment (top view)

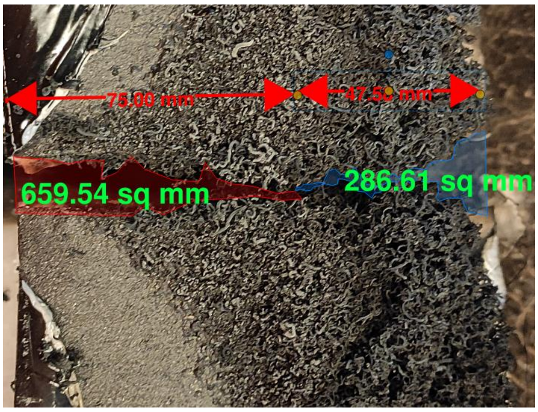


Figure 52 - Area 1 and area 2 of cavity that was not closed after the experiment (Front view)

6.2.3 Data’s from the three set of tests for the Scenario 2

The data for Experiment 1, derived from the three conducted tests, is presented in the Section 6.8. This dataset comprises thermocouple readings, measurements of the remaining gap following the expansion of the intumescent strip, and the percentage of cavity closure that occurred for both "Area 1" and "Area 2."

6.2.4 Discrepancy in test results:

It should be highlighted that the data from test 2 (40.61%) was omitted from the analysis due to the substantial presence of debris from the expanded intumescent material near the burner during this particular test.

6.3 Scenario-3: 30 mm gap between two cavity barriers.

Scenario 3 featured a 30 mm gap between the cavity barriers, as depicted in Figure 53. This system was installed atop the experimental setup, as illustrated in Figure 54. The experiment's duration was set at five minutes, with the timer commencing from the ignition of the propane gas at the cubical burner. The dataset considered for analysis encompassed thermocouple readings, photographs taken throughout the experiment, and measurements taken to assess the expansion of the intumescent strip.

Figure 53 - Cavity barrier blocks installed over the gypsum board keeping a gap of 30 mm.

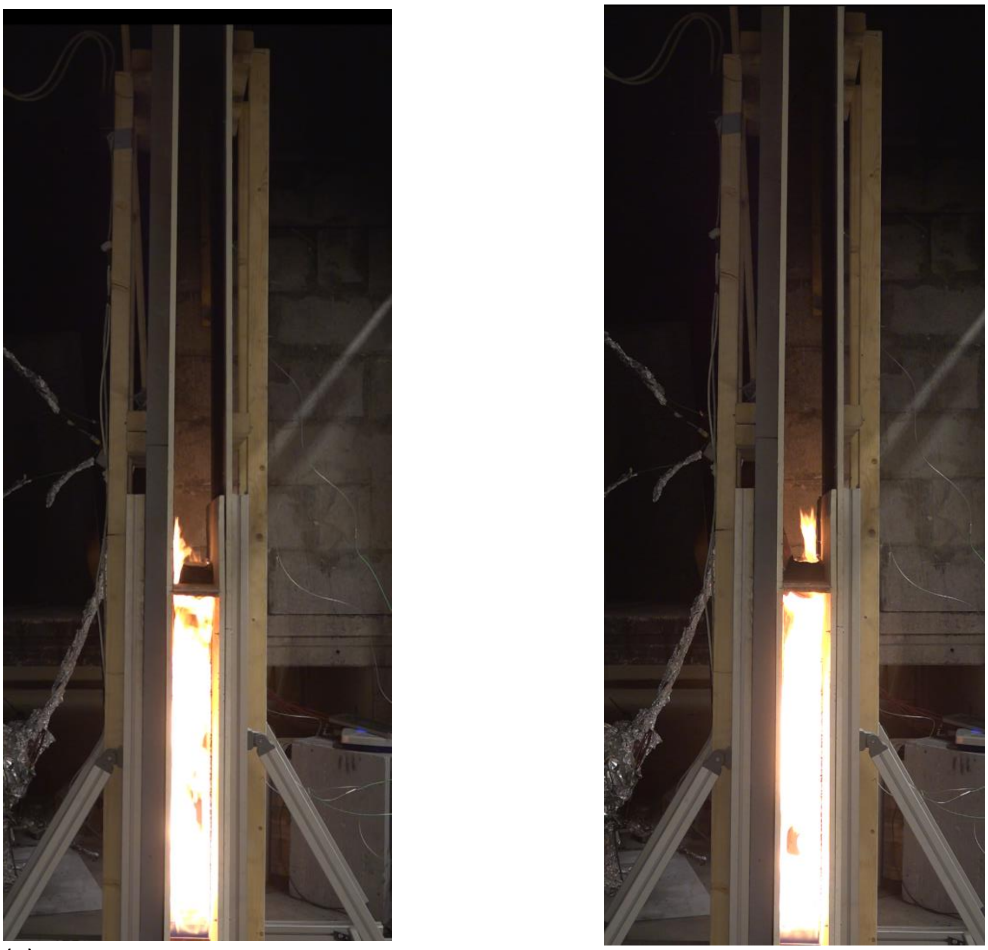
Figure 54 -Cavity barrier blocks installed within the experimental setup with a gap in between.

The configuration of the experimental setup, including the placement of thermocouples, is detailed in Section 5.3.1. To establish the closure time resulting from the expansion of the intumescent strip, we referred to the temperature drops recorded by the thermocouple situated just above the cavity barrier, positioned at a height of 106 mm from the base of the burner and this methodology aligns with the guidance provided in TGD 19.

6.3.1 Observation and Temperature measurements

The video recording of the entire test provides valuable insights into the progression of events. Initially, flames were observed in Zone 2 from approximately 35 to 40 seconds following the ignition of the propane burner. These flames were entering Zone 2 through both "Area 1" and "Area 2," as illustrated in

Figure 59. However, following the 40th second, it became evident that flames were only entering Zone 2 through "Area 1," with no flames passing through "Area 2," as depicted in Figure 55 (b). Moreover, after the 40 second mark, flames were intermittent and eventually ceased in Zone 2 throughout the duration of the experiment.



(a) (b)

Figure 55 - Before and after images of cavity closure during the experiment (a) before at 14th second (b) after at 59th second

Temperature measurements were systematically taken at various locations within both Zone 1 and Zone 2 using thermocouples, in accordance with the details outlined in Section 5.3.1. Specifically, the temperature just below the cavity barrier was actively maintained within the range of 400 °C to 500 °C, with continuous monitoring conducted via a thermocouple situated at a height of 93 cm above the base of the propane burner. The propane gas supply was precisely controlled at a rate of 0.4 g/s.

The temperature readings revealed significant observations. After approximately 35 to 40 seconds, a drop-in temperature within Zone 2 was noted. The moment when this temperature drop occurred for the thermocouple located just above the cavity barrier (at a height of 106 cm from the base of the propane burner) was considered as evidence of the complete cavity closure in "Area 2" due to the expansion of the intumescent material. This pivotal point is marked in the graph by a green dotted line as indicated in Figure 46.

Furthermore, the thermocouple positioned in Zone 2 at a height of 120 cm from the burner base recorded a peak temperature of approximately 190 °C, which did not surpass 200 °C. In contrast, the thermocouple at the height of 106 cm displayed a temperature drop after the intumescent material expansion, reaching 400 °C and then stabilizing within the range of around 250 °C for the remainder of the experiment. Importantly, the thermocouple positioned at the highest point of the experimental setup, situated 183 cm above the base of the propane burner, did not register temperatures exceeding 100 °C.

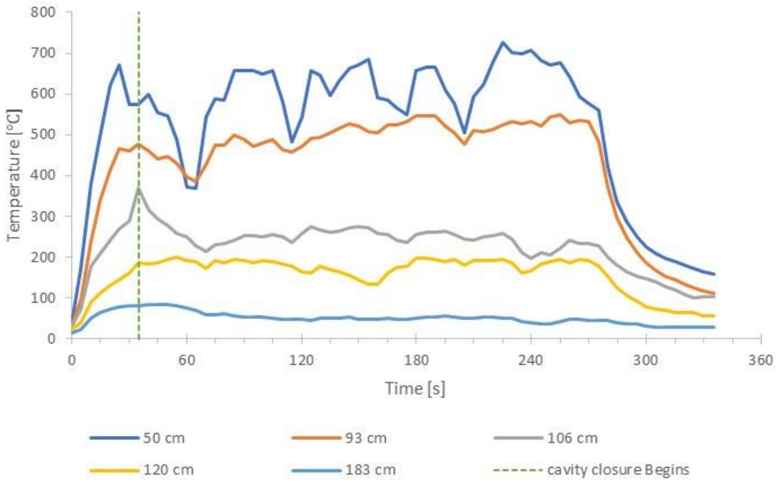
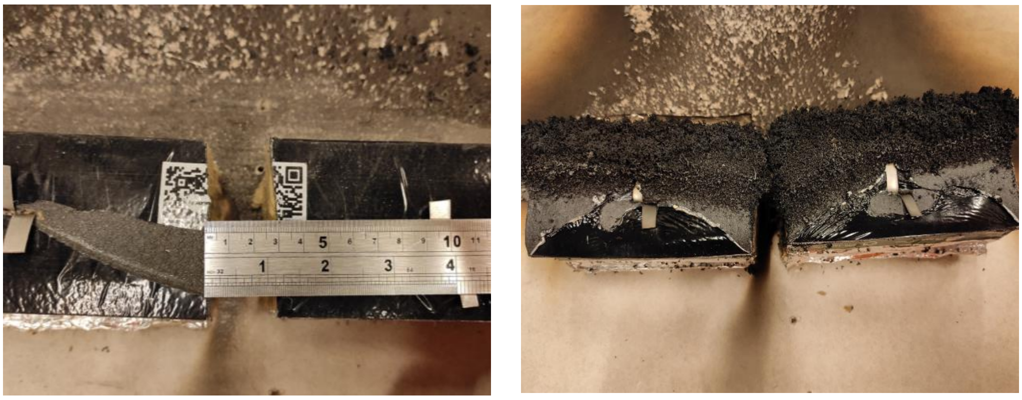


Figure 56 - Thermocouple reading for the experiment with 15 mm gap between the cavity barriers (Test 2)

6.3.2 Expansion area measurement for the Scenario-3

The regions designated for assessing the expansion of the intumescent strip have been elaborated upon in Section 5.3.1. These areas, namely "Area 1" and "Area 2," as delineated in this section, were independently quantified to determine the percentage of closure during the fire. Visual documentation of the pre and post-experiment conditions can be observed in Figure 57, respectively. Figure 58 and

Figure 59 illustrate the measurement of “Area 1” and “Area 2.” The red-coloured area represents Area 1, while the blue-coloured area represents “Area 2.



(a) (b)

Figure 57 - Before and after images of the cavity barrier

The assessment of cavity closure was performed by analysing post-experiment photographs, with the assistance of the Bluebeam Revu x64 Standard software. A measurement error tolerance of 10% was considered during this process.

From the front view as shown in Figure 59 it was observed that after the expansion, the percentage of cavity that remained open in "Area 1" ranged from 45% to 47%. In contrast, for "Area 2," approximately 22% of the cavity remained open.

When viewed from the top perspective as indicated in Figure 58, "Area 1" exhibited a closure percentage of approximately 90%, while "Area 2" had a range of approximately 18%. Notably, during test 3, even though "Area 2" had a top view cavity percentage of 78%, it's significant to point out that there was no continuous presence of flame and smoke in Zone 2 throughout the experiment, despite the cavity opening in "Area 2".

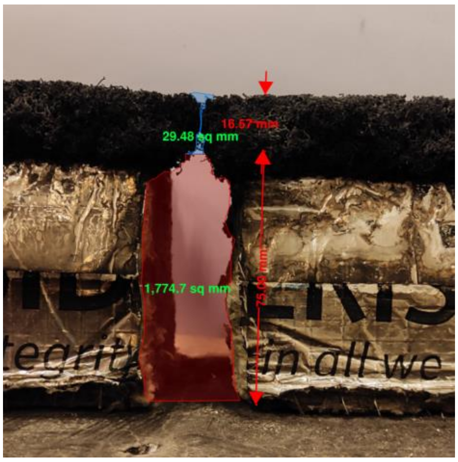


Figure 58 - Area of cavity that was not closed after the experiment (top view)

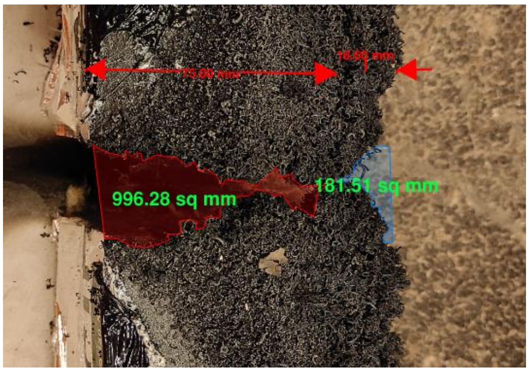


Figure 59 - Area of cavity that was not closed after the experiment (front view)

6.3.3 Data from the three set of tests for the Scenario-3

The data for Scenario 3, obtained from the three conducted tests, is summarized in the Section 6.8. This dataset encompasses thermocouple readings, measurements of the remaining gap following the expansion of the intumescent strip, and the percentage of cavity closure for both "Area 1" and "Area 2".

6.4 Scenario-4: 45 mm gap between two cavity barriers.

In this experimental setup, a gap of 45 mm was introduced between the cavity barriers, as illustrated in Figure 60. This specific configuration was meticulously placed over the experimental arrangement, as visually demonstrated in Figure 61. The experiment spanned a duration of five minutes, commencing with the initiation of the timer at the moment propane gas was ignited at the cubic burner. The dataset employed for subsequent analysis encompassed thermocouple readings, photographs captured at various points during the experiment, and measurements obtained to evaluate the extent of the intumescent strip's expansion.

Figure 60 - Cavity barrier blocks installed over the gypsum board keeping a gap of 45 mm.

Figure 61 -Cavity barrier blocks installed within the experimental setup with a 45 mm gap in between.

6.4.1 Observation and Temperature measurements

The video recording of the entire test provided significant observations. Initially, flames were observed in Zone 2 from approximately 40 to 45 seconds following the ignition of the propane burner. During this time frame, flames entered Zone 2 through both "Area 1" and "Area 2," as depicted in Figure 62(a). Even beyond the 45-second mark, flames continued to enter Zone 2 through both "Area 1" and "Area 2," as shown in Figure 62(b).

It's worth noting that the hot air flow generated by the propane burner had the effect of carrying the expanded intumescent material in "Area 2." Subsequently, this material was drawn out through the provided smoke suction hood situated over the experimental setup.

(a)

(b)

Figure 62 - before and after images of cavity closure (a) before at 14th second (b) after at 57th second

Temperature measurements were meticulously taken at various locations within both Zone 1 and Zone 2, as per the specifications discussed in Section 5.3.2. The temperature control was maintained within the range of 400 °C to 500 °C just below the cavity barrier, and this was continuously monitored using a thermocouple positioned at a height of 93.75 cm from the base of the propane burner. The supply of propane gas was precisely controlled at a rate of 0.4 g/s.

The temperature data revealed significant findings. After approximately 40 to 45 seconds, there was a slight drop in temperature within Zone 2. The moment when this temperature drop occurred for the thermocouple placed just above the cavity barrier, at a height of 106 cm from the base of the propane burner, was considered indicative of the completion of intumescent strip expansion for "Area 2." This critical point is highlighted in the graph with a green dotted line.

The temperature drop for the thermocouple reading as indicated in the green dotted line as shown in Figure 63 that was placed above the cavity barrier (at 106 mm height from the base of burner) as per the guidance from TGD 19 was considered as an evidence to show the closure of cavity by the expansion of intumescent strip for the “Area 2.”

Additionally, the thermocouple located in Zone 2 at a height of 120 cm from the bottom of the burner recorded a peak temperature of approximately 250 °C, which never exceeded 300 °C. Conversely, the thermocouple at the height of 106 cm displayed a temperature drop after the intumescent material expansion, reaching 400 °C and subsequently stabilizing within the range of around 250 °C to 300 °C for the remainder of the experiment. Notably, the thermocouple positioned at the highest point of the experimental setup, situated 183 cm above the base of the propane burner, did not register temperatures exceeding 100°C.

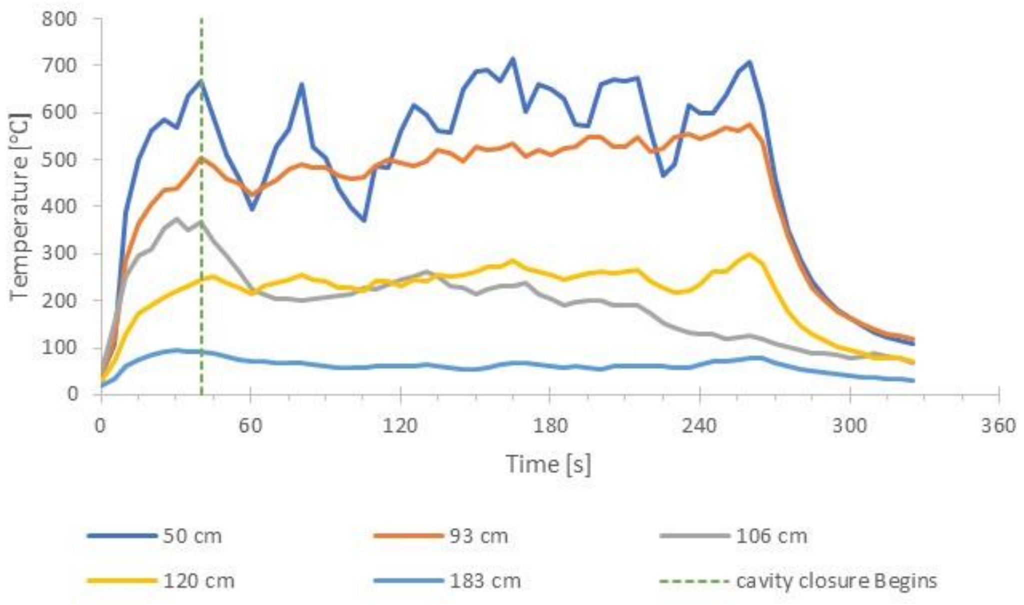
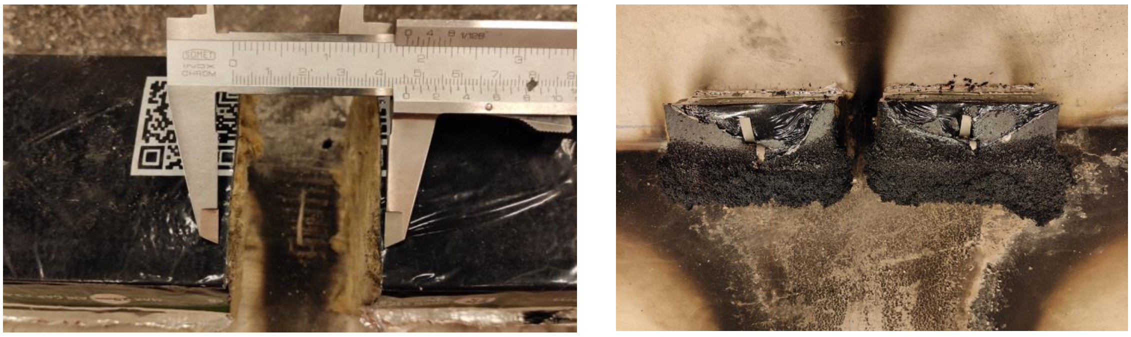


Figure 63 - Thermocouple reading for the experiment with 15 mm gap between the cavity barriers

6.4.2 Expansion area measurement for the Scenario-4

The specific regions selected for assessing the expansion of the intumescent strip have been detailed in Section 5.3.3. These regions, denoted as "Area 1" and "Area 2" as outlined in Section 5.3.3 were individually measured to determine the percentage of closure that occurred during the fire. Visual documentation of the conditions before and after the experiment can be referenced in Figure 64.



(a) (b)

Figure 64 - Before and after pictures of cavity barrier arrangement for the scenario 4 (a) before (b) after

The assessment of cavity closure was conducted by analysing post-experiment photographs with the assistance of the Bluebeam Revu x64 Standard software. A measurement error tolerance of 10% was taken into consideration during the area measurements. Figure 65 and Figure 66 provide visual representations of the measurement of both “Area 1” and “Area 2.” “Area 1” is denoted by the red-coloured region, whereas “Area 2” is indicated by the blue-coloured area.

From the front view, it was observed that after the expansion, the percentage of cavity that remained open in "Area 1" was approximately 73%. In the case of "Area 2," around 85% of the cavity remained opens.

When viewed from the top perspective, "Area 1" displayed a closure percentage of approximately 98%, while "Area 2" ranged from 45% to 50%. Importantly, during test 2 and test 3, it was noted that the expanded intumescent material was carried away by the hot air from "Area 2."

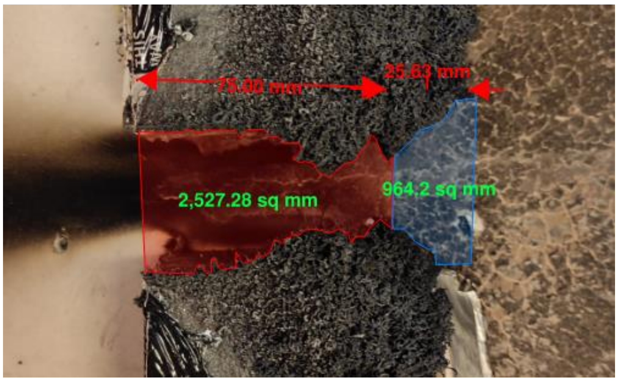


Figure 65 - Area of cavity that was not closed after the experiment (front view)

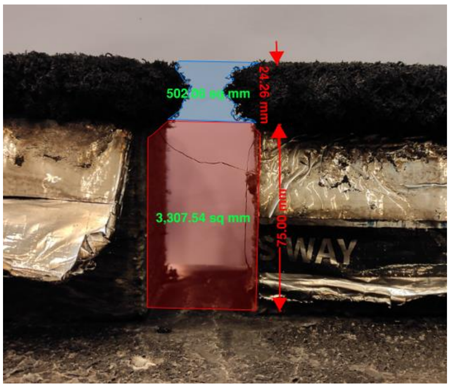


Figure 66 - Area of cavity that was not closed after the experiment (Top view)

6.4.3 Data from the three set of tests for the scenario 4

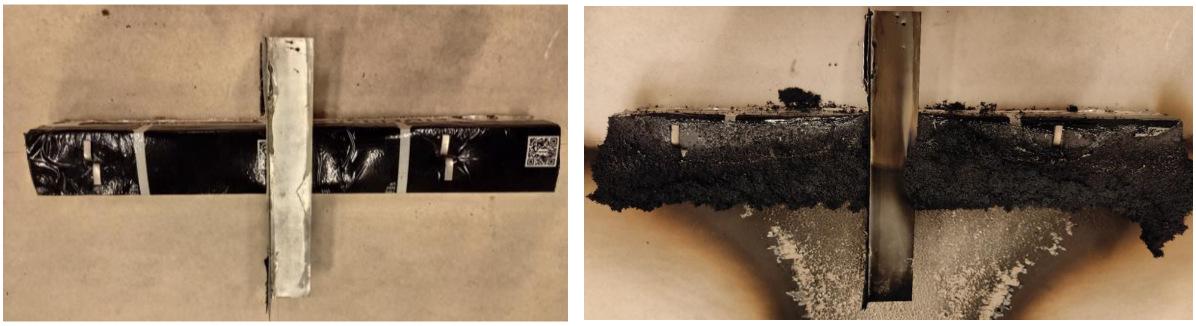
The data for Scenario 4, derived from the three conducted tests, is summarized in the Section 6.8. This dataset comprises thermocouple readings, measurements of the remaining gap following the expansion of the intumescent strip, and the percentage of cavity closure that occurred.

6.5 Scenario 5: Providing a blockage in front of cavity barriers.

Scenario 5 was designed to explore the functionality of cavity barriers when an obstruction is present in front of the intumescent strip. To simulate this scenario, an L-shaped steel angle with dimensions specified in Section: 5.4.1 was installed over the experimental setup, as illustrated in Figure 67(a). The experiment was conducted over a duration of five minutes, commencing with the ignition of propane gas at the cubic burner. Data for analysis encompassed thermocouple readings, photographic documentation, and measurements of the expanded intumescent strip.

6.5.1 Observations and Temperature measurements

The evaluation of intumescent strip expansion is conducted within defined regions, as detailed in Section 5.4.3. These specified areas, referred to as "Area 1" within the same section, are individually examined to measure the degree of closure achieved during a fire incident. To facilitate a visual representation of this assessment, you can refer to Figure 67, which provides photographic documentation depicting the condition of the cavity barrier both before and after exposure to a fire.

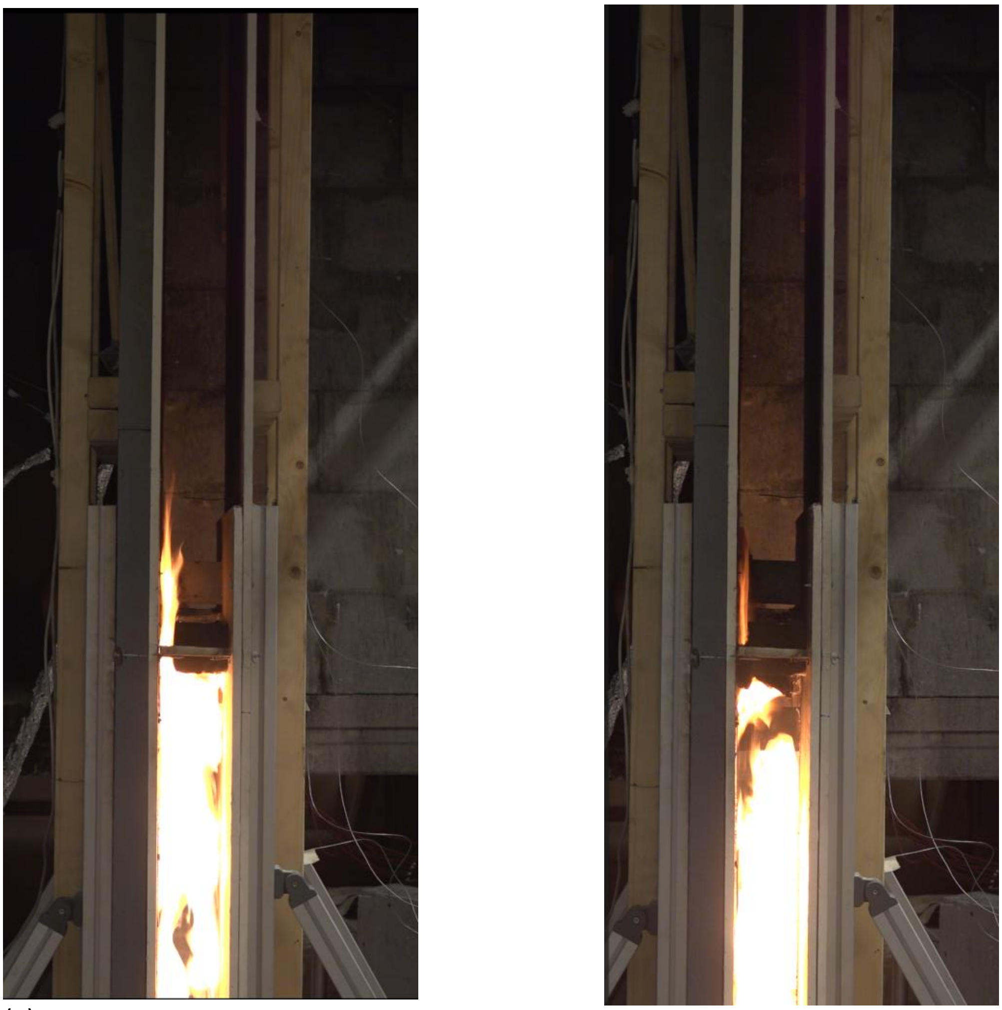


(a) (b)

Figure 67 - before and after pictures for the experiment (a) before (b) after

The analysis of the experiment's video footage reveals that the intumescent strip expansion was completed between the 25th and 30th seconds after igniting the propane burner. This expansion partially closed "Area 1." Subsequently, visible flames were observed in Zone 2 through "Area 1," as indicated in Figure 68(a). However, the temperature in Zone 2 dropped below 100 °C after the intumescent strip expansion was completed.

During the initial ignition stages, flames were clearly visible through "Area 1" until the 25th second, as depicted in Figure 69(a). As approached the 30-second mark, the visibility of flames in Zone 2 gradually decreased, as shown in Figure 68(b). Beyond the 30-second mark, smoke accompanied by small flames emerged through "Area 1," as illustrated in Figure 68(b).



(a) (b)

Figure 68 - before and after pictures of expansion of intumescent material (a) before (b) after

Temperature measurements were systematically carried out at various locations within both Zone 1 and Zone 2 using thermocouples, as outlined in Section 5.4.2. Specifically, the temperature just beneath the cavity barrier was maintained within the range of 400 °C to 500 °C. This temperature range was consistently monitored by a thermocouple positioned at a height of 93 cm from the base of the propane burner, with a controlled propane gas supply rate of 0.4 g/s.

The specific placement of thermocouples within the experimental setup is detailed in Section 5.4.2. The recorded temperature drops for the thermocouple located just above the cavity barrier (at a height of 106 mm from the bottom of the burner), in accordance with the guidelines from TGD 19, were considered as evidence demonstrating the closure time of "Area 1" due to the expansion of the intumescent strip. This significant event is highlighted in the graphs using a green dotted line, as indicated in Figure 46.

Moreover, the two additional thermocouples situated within Zone 2 consistently reported peak temperatures below 120 °C, never exceeding the critical threshold of 200 °C. Furthermore, the thermocouple positioned at a height of 106 cm, just above the cavity barrier, exhibited a reduction in temperature to 200 °C following the expansion of the intumescent material, occurring between 55 to 60 seconds into the experiment. Lastly, the thermocouple positioned at the highest point of the experimental setup, located 183 cm above the base of the propane burner, did not register temperatures exceeding 100 °C.

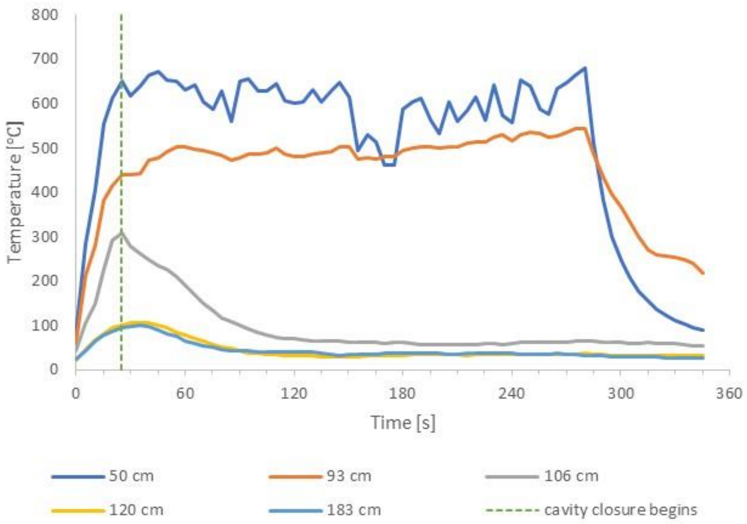
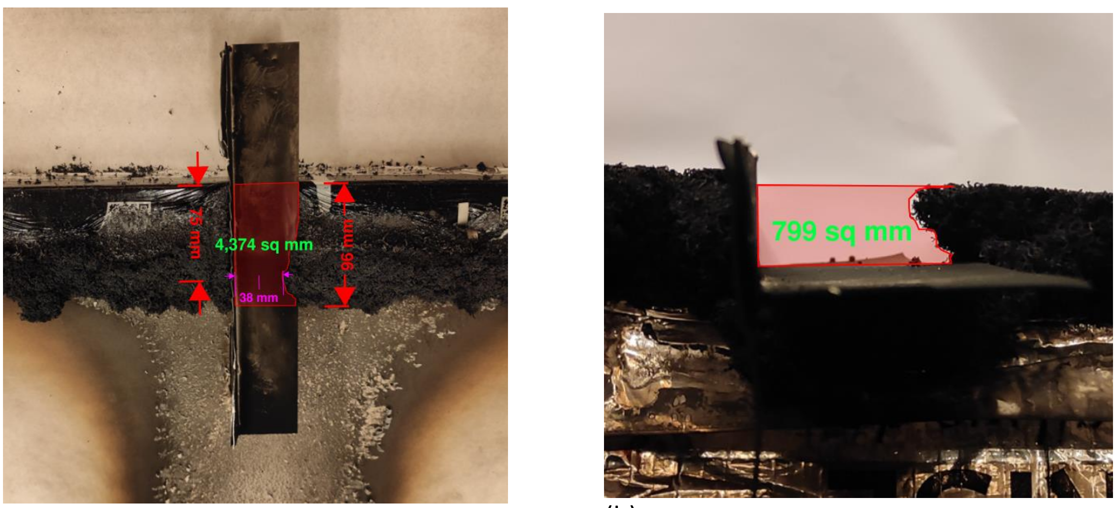


Figure 69 - Thermocouple reading for the experiment with 15 mm gap between the cavity barriers

6.5.2 Intumescent material expansion measure

The determination of the cavity closure area was performed through the analysis of post-experiment photographs, with the assistance of the Bluebeam Revu x64 Standard software. Figure 70 offer visual depictions of the measurement process for both Area 1 and Area 2. The red-coloured region signifies Area 1, while the blue-coloured area represents Area 2.

From the front view, the analysis demonstrated that within "Area 1," the proportion of the cavity that remained open ranged from 86% to 91% following the expansion of the intumescent strip. When viewed from a top-down perspective, the assessment of cavity closure in "Area 1" indicated a range of 63% to 66%. These measurements are visually represented in Figure 70.



(a) (b)

Figure 70 - Area measurement of the installed cavity barrier with L angle (a) front view (b) top view

6.5.3 Data’s from the three set of tests for the Scenario-5

The data for Scenario 5, which encompasses results obtained from three separate tests, is presented in the Section 6.8. This dataset includes thermocouple readings, measurements of the remaining gap after the intumescent strip's expansion, and the percentage of cavity closure specifically within "Area 1."

6.5.4 Discrepancy in tests

During the course of Test 2, the presence of debris from the expanded intumescent material near the burner was observed after the experiment concluded. This observation is seen as a potential factor contributing to variations in the temperature curve, particularly the drop in temperature recorded by the thermocouple positioned at a height of 106 cm after 50 seconds into the experiment. Additionally, the measurement of the percentage of open cavity for the front view indicated a value of 97%. This suggests that the debris found near the burner likely originated from the expanded intumescent material and contributed to the observed gap, thus impacting the overall temperature measurements and cavity closure assessment.

6.6 Scenario 6: OSCB installed with a 50% wider gap

Scenario 6 was designed to investigate the performance of cavity barriers when a larger cavity exists in front of the intumescent strip. In this scenario, an additional gap, equivalent to 50% of the original gap size, was intentionally created in front of the cavity barrier, as elaborated in Section 5.5. The experiment was conducted over a five-minute duration, with the timer commencing at the ignition of propane gas within the cubic burner. The data considered for subsequent analysis included thermocouple readings, photographic documentation, and measurements of the expanded intumescent strip.

6.6.1 Observations and Temperature measurements

The evaluation of intumescent strip expansion is focused on particular regions, as detailed in Section 5.5.1. These specified areas, identified as "Area 1" within the same section, are individually evaluated to measure the degree of closure achieved during a fire event. To gain a visual understanding of this assessment, you can refer to Figure 71, which provides photographic documentation illustrating the condition of the cavity barrier both before and after exposure to a fire.

(a) (b)

Figure 71 - before and after images of the cavity barrier installed over the gypsum board (a) before (b) after

The analysis of the experiment's video footage reveals that between the 17th and 20th seconds after igniting the propane burner, the intumescent strip expansion was completed, partially closing the cavity. Following this expansion, no visible flames were observed in Zone 2 through "Area 2." However, a layer of smoke was visible in Zone 2 through "Area 1," accompanied by smaller and intermittent flames.

During the initial ignition stages, flames were evident in both "Area 1" and "Area 2" until the 20th second, as noted. Gradually, as approached the 30-second mark, the visibility of flames in Zone 2 decreased, as depicted in Figure 72(a). Beyond the 30-second mark, smoke emerged through "Area 1," along with small flames, as illustrated in Figure 72(b).


(a)

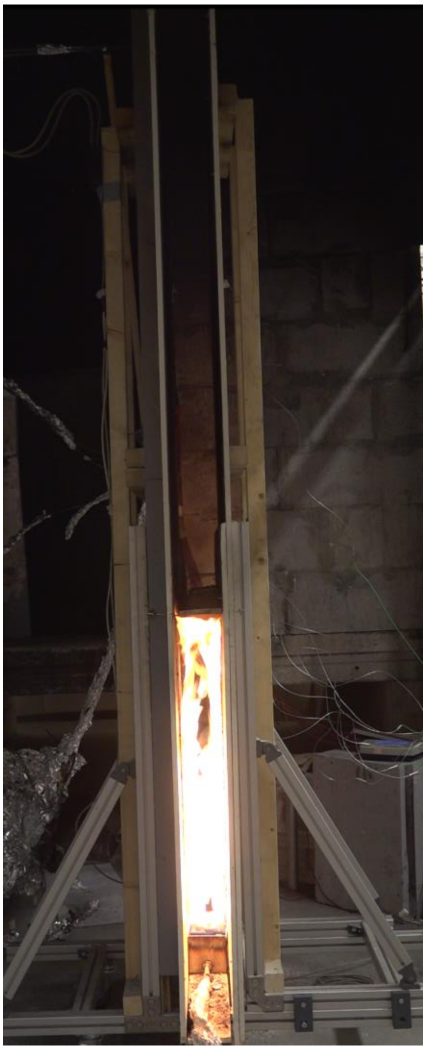

(b)

Figure 72 - Before and after the expansion of intumescent material (a) before expansion at 16th second (b) after expansion at 76th second

Temperature measurements were systematically carried out at various locations within both Zone 1 and Zone 2 using thermocouples, as detailed in Section 5.5.2. Specifically, the temperature just beneath the cavity barrier was maintained within the range of 400 °C to 500 °C. This temperature range was continuously monitored by a thermocouple positioned at a height of 93 cm from the base of the propane burner, with a controlled propane gas supply rate of 0.4 g/s.

The precise placement of thermocouples within the experimental setup is discussed in Section 5.5.2. The recorded temperature drops for the thermocouple located just above the cavity barrier (at a height of 106 mm from the bottom of the burner), following the guidelines from TGD 19, were considered as evidence indicating the closure time of "Area 2" due to the expansion of the intumescent strip. This significant event is highlighted in the graphs using a green dotted line, as indicated in Figure 73.

Moreover, the two additional thermocouples situated within Zone 2 consistently reported peak temperatures below 180 °C, never exceeding the critical threshold of 200 °C. Furthermore, the thermocouple positioned at a height of 106.25 cm exhibited a temperature decrease to 200 °C following the expansion of the intumescent material, occurring between 55 to 60 seconds into the experiment. Lastly, the thermocouple at the highest point of the experimental setup, located 183 cm above the base of the propane burner, did not record temperatures exceeding 100 °C.

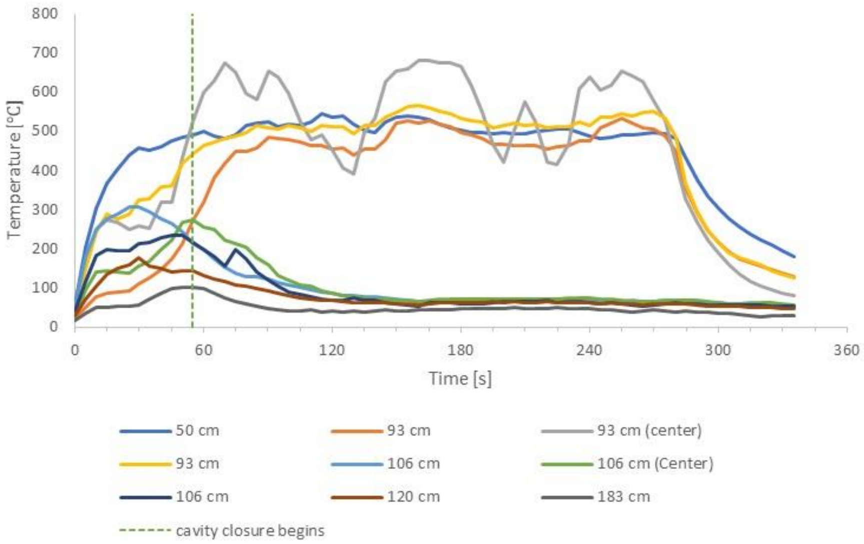


Figure 73 - Thermocouple reading for the scenario 6

6.6.2 Intumescent material expansion measure

The quantification of cavity closure area was systematically carried out using post-experiment photographs and was facilitated by the Bluebeam Revu x64 Standard software. Analysis from a front view perspective demonstrated that within "Area 1," the proportion of the cavity that remained open ranged from 16% to 22% following the expansion of the intumescent strip.

This observation indicates that despite the presence of some remaining open cavity space within "Area 1," the expanded intumescent material effectively served its purpose by preventing the intrusion of flames into Zone 2 through this region within the experimental setup. The front view of the cavity barrier after the test is shown in the Figure 74 with the area of intumescent material which was not expanded during the test.

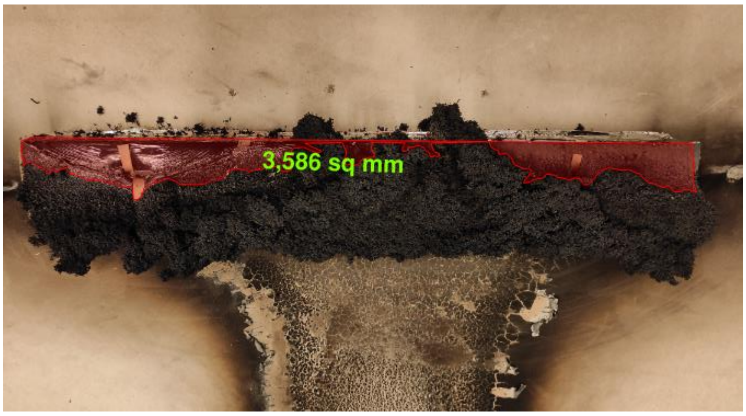


Figure 74 - Area measurement after the expansion intumescent material.

The intumescent material area mentioned earlier did not expand due to a temperature drop that occurred in Zone 2 following the closure of the cavity. This discrepancy becomes evident when comparing the timing of the temperature drop as indicated in Figure 73 with the visual evidence provided in the video footage. The temperature drop served as a clear indicator of the moment when the intumescent material ceased expanding, and this aligns with the video evidence of the experiment.

6.6.3 Data's from the three set of tests for the experiment 6

The data for Scenario 6, derived from the three conducted tests, is presented in the Section 6.8. This dataset comprises thermocouple readings, measurements of the remaining gap following the expansion of the intumescent strip, and the percentage of cavity closure that occurred for "Area 1."

6.7 Scenario-7: Cavity barrier placed at corners

In the context of examining cavity barrier performance in corner installations, a structured investigation was conducted in Scenario 7. To replicate this scenario, a steel plate was expertly bent to a 90-degree angle, forming a corner where the cavity barrier was installed in accordance with the manufacturer's stipulated guidelines, as visually depicted in Figure 75(a). The experimental phase encompassed a precisely timed duration of five minutes, with the timer initiating upon the ignition of propane gas within the cubic burner. The dataset selected for subsequent comprehensive analysis encompassed thermocouple readings, photographic documentation, and measurements pertaining to the expansion of the intumescent strip.

6.7.1 Observations and Temperature measurements

The evaluation of intumescent strip expansion involves distinct regions, as detailed in Section 5.6. These specified areas, referred to as "Area 1" within Section 5.6, are evaluated separately to measure the extent of closure achieved during a fire event. For a visual representation of this assessment, please refer to Figure 76, which provide photographic documentation depicting the condition of the cavity barrier both prior to and following exposure to a fire.

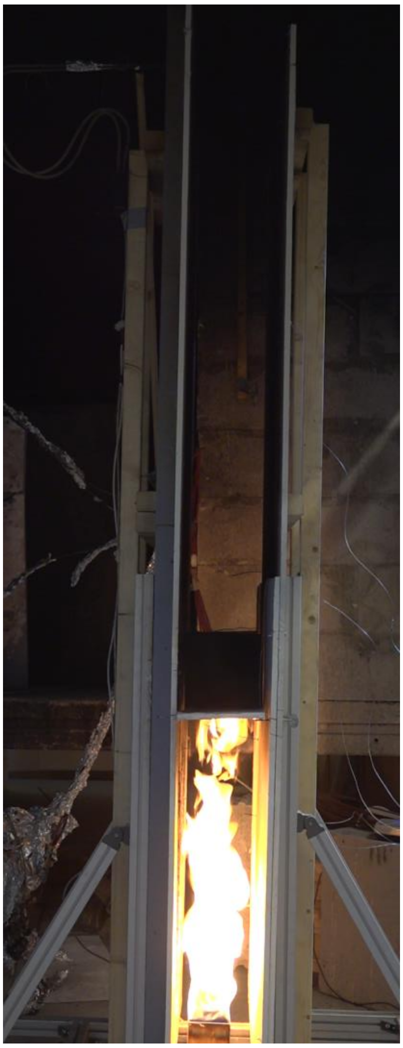
(a) (b)

Figure 75 - Before and after image showing the OSCB expansion for the scenario 7 (a) before (b) after

(a) (b)

Figure 76 - The OSCB after the test for the scenario 7 (a) top view (b) front view

The experiment's video footage reveals that intumescent strip expansion completed between the 75th and 90th seconds after igniting the propane burner. During this time frame, the intumescent strip partially closed the cavity. Following this expansion, there was no visible flame in Zone 2 through "Area 1." However, a smoke layer was observed in Zone 2 through "Area 1,". Due to the presence of steel plate the flames coming through the gap was not visible.



(a)

(b)

Figure 77 - Before and after the intumescent material expansion (a) before the expansion at 16th second (b) after expansion at 45th second

Temperature measurements were conducted at various locations within both Zone 1 and Zone 2, as described in 5.6.1. Specifically, a thermocouple positioned at a height of 93 cm from the base of the propane burner continuously monitored the temperature just below the cavity barrier, maintaining it within the range of 400 °C to 500 °C.

The experimental setup showing the location of thermocouples are discussed in the Section 5.6.2. The temperature drops for the thermocouple, placed just above the cavity barrier (at 106 mm height from bottom of the burner) as per the guidance from TGD 19 [29] guidelines, was considered as an evidence to show the closure time of the cavity due to the expansion of intumescent strip. This point is highlighted in green dotted line in the graphs as shown in the Figure 78.

The temperature data reveals a significant observation. After 75 seconds into the experiment, there was a noticeable decrease in temperature within Zone 2. The point at which this temperature drop occurred for the thermocouple located just above the cavity barrier, precisely at a height of 106 cm from the bottom of the propane burner, was identified as the moment when "Area 2" achieved complete cavity closure due to the expansion of the intumescent material.

Moreover, the other two thermocouples situated within Zone 2 recorded peak temperatures below 180 °C, never exceeding the 200 °C threshold. Additionally, the thermocouple positioned at a height of 106cm exhibited a decrease in temperature to 200 °C after the expansion of the intumescent material, occurring between 75 to 90 seconds. Lastly, the thermocouple located at the highest point of the experimental setup, positioned 183 cm above the base of the propane burner, did not register temperatures exceeding 100 °C throughout the experiment.

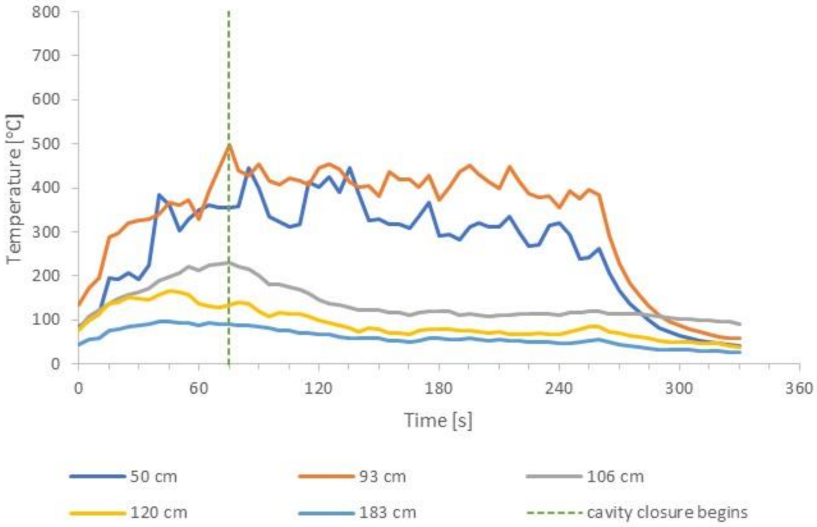


Figure 78 - Thermocouple reading for the experiment with 15 mm gap between the cavity barriers

6.7.2 Data's from the three set of tests for the Scenario 7

The data for Scenario 7, derived from the three conducted tests, is presented in the Section 6.8. This dataset comprises thermocouple readings, measurements of the remaining gap following the expansion of the intumescent strip, and the percentage of cavity closure that occurred for both "Area 1" and "Area 2."

6.8 Test Data from the Experiments

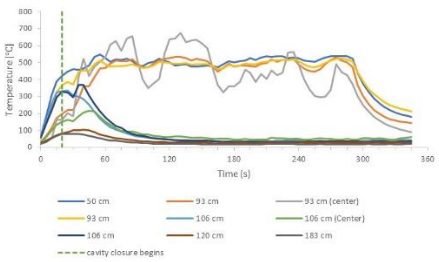
Table 3 Data's from the three set of tests for the Scenario 1

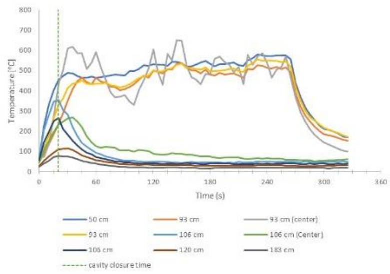
Test 1

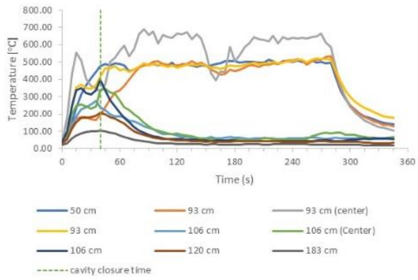
Test 2

Test 3

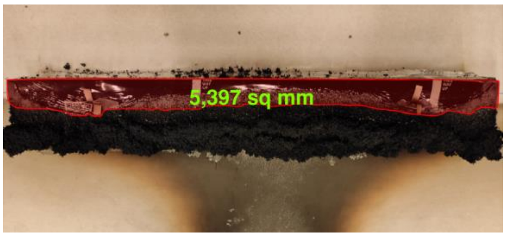
Thermocouple readings

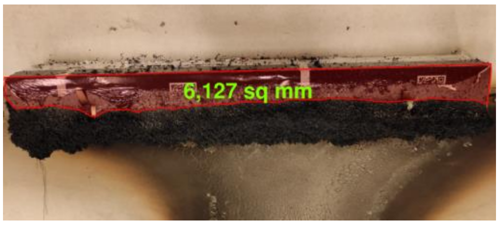


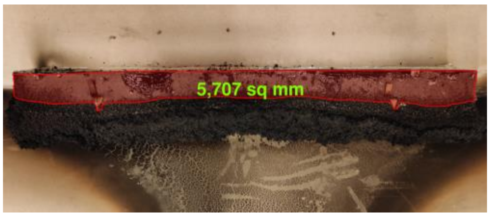




Images showing the area calculation by scaling the image using Bluebeam Revu software







Percentage of cavity closure calculated (Front View)

Test 1

Area measurments	**Values**	**Units**
length	300	mm
breadth	75	mm
initial area	22500	sq mm
unexpanded area of intumescent strip	5379	sq mm
% of area not expanded	**23.91**	%
% of area expanded	76.09	%

Test 2

Area measurments	**Values**	**Units**
length	300	mm
breadth	75	mm
initial area	22500	sq mm
unexpanded area of intumescent strip	6127	sq mm
% of area not expanded	**27.23**	%
% of area expanded	72.77	%

Test 3

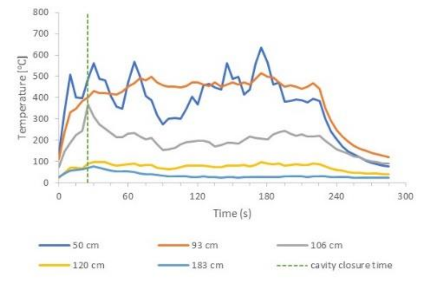
Area measurments	**Values**	**Units**
length	300	mm
breadth	75	mm
initial area	22500	sq mm
unexpanded area of intumescent strip	5707	sq mm
% of area not expanded	**25.36**	%
% of area expanded	74.64	%

Table 4 Data's from the three set of tests for the Scenario 2

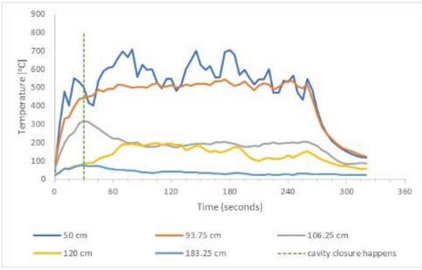
Test 1 | Test 2 | Test 3

Thermocouple readings

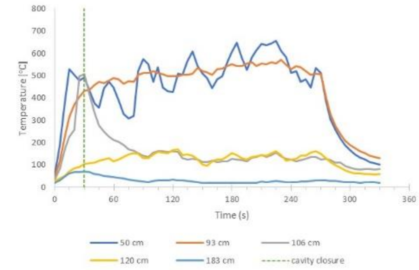
Test 1



Test 2

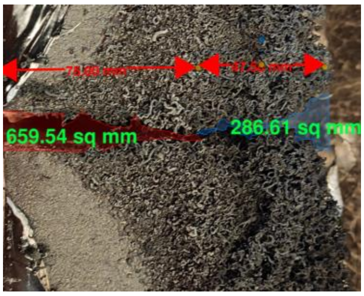


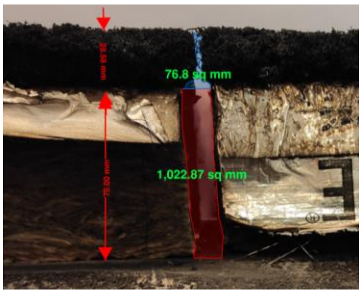
Test 3



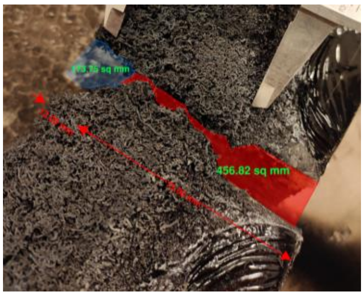
Images showing the area calculation by scaling the image using Bluebeam Revu software

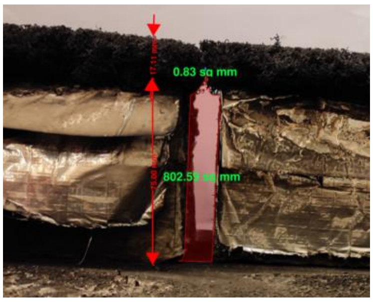
Test 1



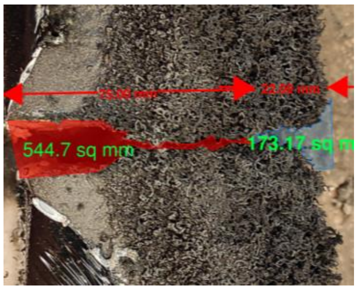


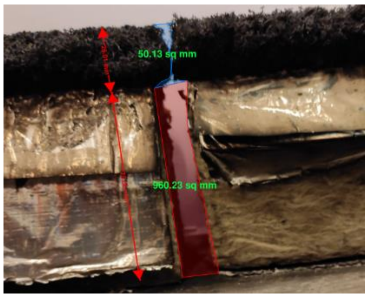
Test 2





Test 3





Percentage of cavity closure calculated (Front View)

Test 1 – Area 1 (front view)

	Values	Units
Initial length	75	mm
initial breadth	15	mm
Initial Area	1125	sq mm
Area without closure after expansion	659.5	sq mm
% of open cavity	**58.62**	%
% of closure	41.38	%

Test 2 – Area 1 (Front view)

	Values	Units
Initial length	75	mm
initial breadth	15	mm
Initial Area	1125	sq mm
Area without closure after expansion	456.82	sq mm
% of open cavity	**40.61**	%
% of closure	59.39	%

Test 3 – Area 1 (Front view)

	Value	Units
Initial length	75	mm
initial breadth	15	mm
Initial Area	1125	sq mm
Area without closure after expansion	544.7	sq mm
% of open cavity	**48.42**	%
% of closure	51.58	%

Area 2 (front view)

	Values	Units
Initial length	47	mm
initial breadth	15	mm
Initial Area	705	sq mm
Area without closure after expansion	286.62	sq mm
% of open cavity	**40.66**	%
% of closure	59.34	%

Area 2 (Front view)

	Values	Units
Initial length	12	mm
initial breadth	15	mm
Initial Area	180	sq mm
Area without closure after expansion	173.7	sq mm
% of open cavity	**96.50**	%
% of closure	3.50	%

Area 2 (Front view)

	Value	Units
Initial length	22	mm
initial breadth	15	mm
Initial Area	330	sq mm
Area without closure after expansion	173.17	sq mm
% of open cavity	**52.48**	%
% of closure	47.52	%

Percentage of cavity closure calculated (Top View)

Area 1 (Top view)

	Values	Units
Initial length	75	mm
initial breadth	15	mm
Initial Area	1125	sq mm
Area without closure after expansion	1022.8	sq mm
% of open cavity	**90.92**	%
% of closure	9.08	%

Area 1 (top view)

	Values	Units
Initial length	75	mm
initial breadth	15	mm
Initial Area	1125	sq mm
Area without closure after expansion	802.5	sq mm
% of open cavity	**71.33**	%
% of closure	28.67	%

Area 1 (Top view)

	Value	Units
Initial length	75	mm
initial breadth	15	mm
Initial Area	1125	sq mm
Area without closure after expansion	960.2	sq mm
% of open cavity	**85.35**	%
% of closure	14.65	%

Area 2 (Top view)

	Values	Units
Initial length	28.58	mm
initial breadth	15	mm
Initial Area	428.7	sq mm
Area without closure after expansion	76.8	sq mm
% of open cavity	**17.91**	%
% of closure	82.09	%

Area 2 (top view)

	Values	Units
Initial length	17.11	mm
initial breadth	15	mm
Initial Area	256.65	sq mm
Area without closure after expansion	0.83	sq mm
% of open cavity	**0.32**	%
% of closure	99.68	%

Area 2 (Top view)

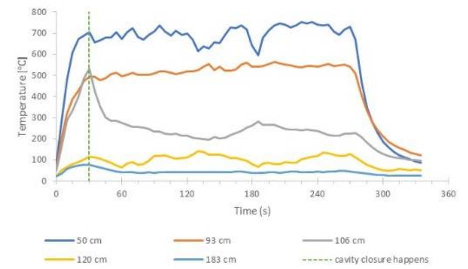
	Value	Units
Initial length	26.01	mm
initial breadth	15	mm
Initial Area	390.15	sq mm
Area without closure after expansion	50.13	sq mm
% of open cavity	**12.85**	%
% of closure	87.15	%

Table 5 Data's from the three set of tests for the Scenario 3

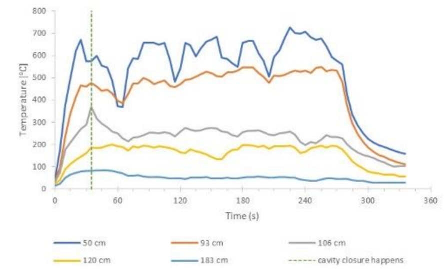
Test 1 | **Test 2** | **Test 3**

Thermocouple readings

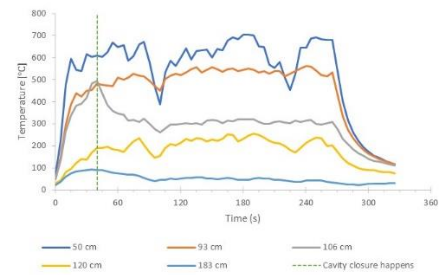
Test 1



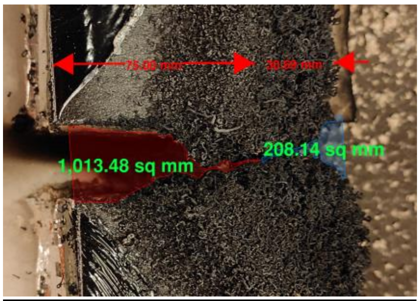
Test 2

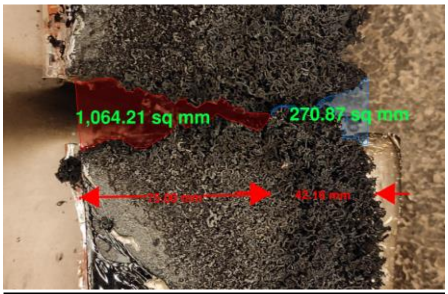


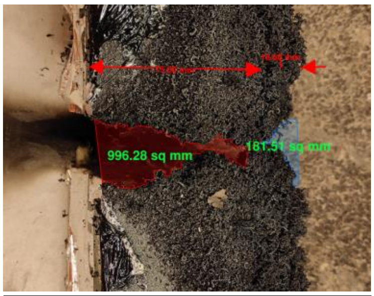
Test 3

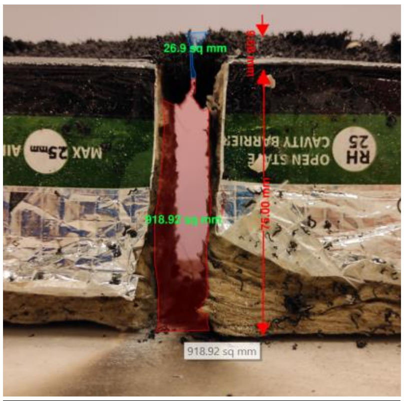


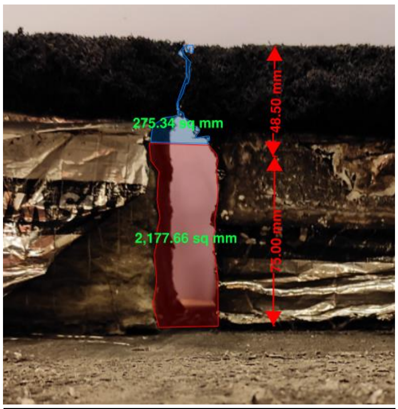
Images showing the area calculation by scaling the image using Bluebeam Revu software

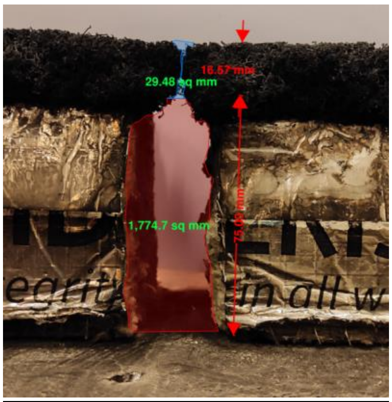












Percentage of cavity closure calculated (Front View)

Test 1 – Area 1 (Front view)

	Values	Units
Initial length	75	mm
initial breadth	30	mm
Initial Area	2250	sq mm
Area not closed after expansion	1013	sq mm
% of open Cavity	**45.02**	%
% of closure	54.98	%

Test 2 – Area 1 (Front view)

	Values	Units
Initial length	75	mm
initial breadth	30	mm
Initial Area	2250	sq mm
Area without closure after expansion	1064	sq mm
% of open cavity	**47.29**	%
% of closure	52.71	%

Test 3 – Area 1 (Front view)

	Values	Units
Initial length	75	mm
initial breadth	30	mm
Initial Area	2250	sq mm
Area without closure after expansion	996	sq mm
% of open cavity	**44.27**	%
% of closure	55.73	%

Area 2 (Front view)

	Values	Units
Initial length	30.6	mm
initial breadth	30	mm
Initial Area	918	sq mm
Area not closed after expansion	208	sq mm
% of open Cavity	**22.66**	%
% of closure	77.34	%

Area 2 (Front view)

	Values	Units
Initial length	42	mm
initial breadth	30	mm
Initial Area	1260	sq mm
Area without closure after expansion	279.9	sq mm
% of open cavity	**22.21**	%
% of closure	77.79	%

Area 2 (Front view)

	Values	Units
Initial length	19	mm
initial breadth	30	mm
Initial Area	570	sq mm
Area without closure after expansion	181.5	sq mm
% of open cavity	**31.84**	%
% of closure	68.16	%

Percentage of cavity closure calculated (Front View)

Area 1 (Top view)

	Values	Units
Initial length	75	mm
initial breadth	30	mm
Initial Area	2250	sq mm
Area not closed after expansion	2177	sq mm
% of open Cavity	**96.76**	%
% of closure	3.24	%

Area 1 (Top view)

	Values	Units
Initial length	75	mm
initial breadth	30	mm
Initial Area	2250	sq mm
Area without closure after expansion	2177	sq mm
% of open cavity	**96.76**	%
% of closure	3.24	%

Area 1 (Top view)

	Values	Units
Initial length	75	mm
initial breadth	30	mm
Initial Area	2250	sq mm
Area without closure after expansion	1774.7	sq mm
% of open cavity	**78.88**	%
% of closure	21.12	%

Area 2 (Top view)

	Values	Units
Initial length	49	mm
initial breadth	30	mm
Initial Area	1470	sq mm
Area not closed after expansion	275	sq mm
% of open Cavity	**18.71**	%
% of closure	81.29	%

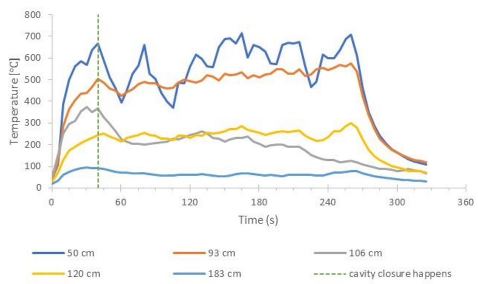
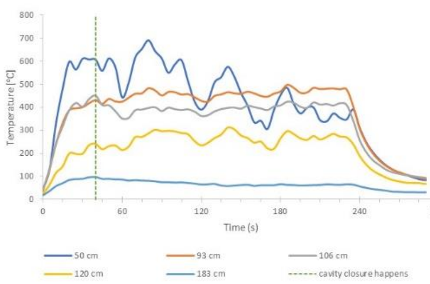
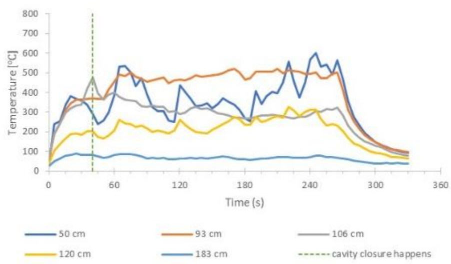
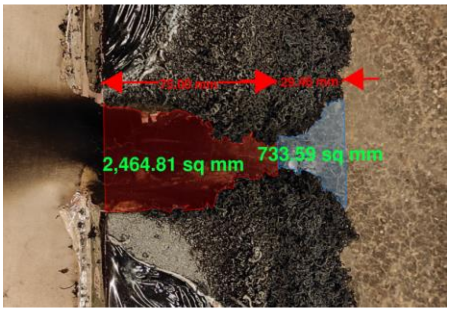
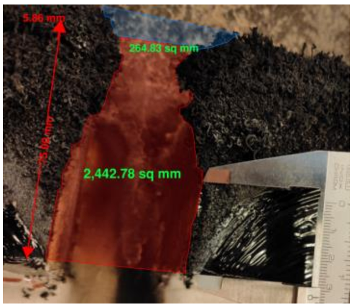
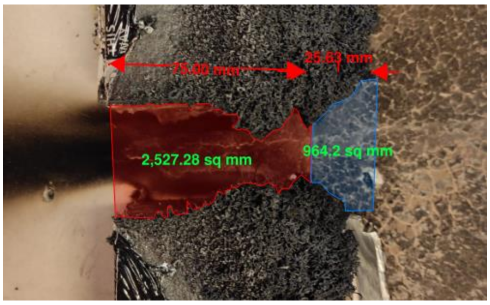
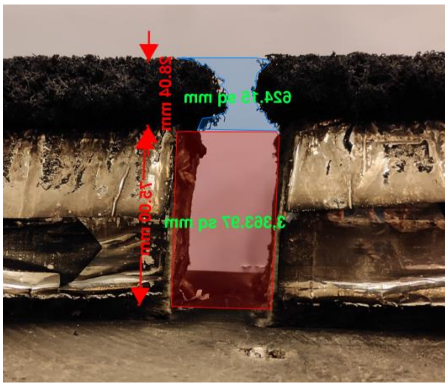
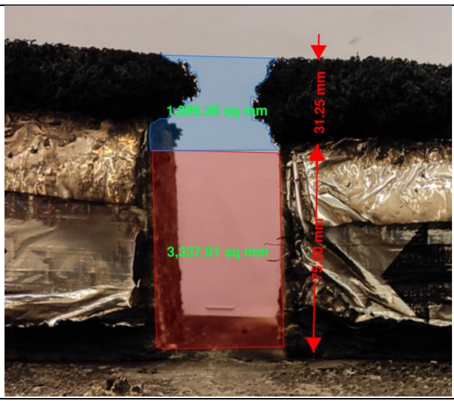
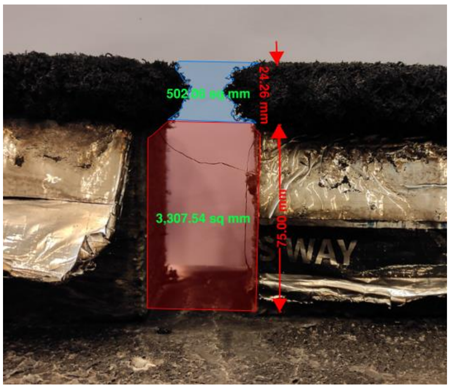
Area 2 (Top view)

	Values	Units
Initial length	48.5	mm
initial breadth	30	mm
Initial Area	1455	sq mm
Area without closure after expansion	275.3	sq mm
% of open cavity	**18.92**	%
% of closure	81.08	%

Area 2 (Top view)

	Values	Units
Initial length	17	mm
initial breadth	30	mm
Initial Area	510	sq mm
Area without closure after expansion	30	sq mm
% of open cavity	**5.88**	%
% of closure	94.12	%

Table 6 Data's from the three set of tests for the Scenario 4

Test 1	**Test 2**	**Test 3**
Thermocouple readings		
		
Images showing the area calculation by scaling the image using Bluebeam Revu software (Front view)		
		
Images showing the area calculation by scaling the image using Bluebeam Revu software (Top view)		
		
Percentage of cavity closure calculated		

Test 1 – Area 1 (Front view)

	Values	Units
Initial length	75	mm
initial breadth	45	mm
Initial Area	3375	sq mm
Area without closure after expansion	2464.8	sq mm
% of open cavity	**73.03**	%
% of closure	26.97	%

Test 2 – Area 1 (Front view)

	Values	Units
Initial length	75	mm
initial breadth	45	mm
Initial Area	3375	sq mm
Area without closure after expansion	2442	sq mm
% of open cavity	**72.36**	%
% of closure	27.64	%

Test 3 – Area 1 (Front view)

	Values	Units
Initial length	75	mm
initial breadth	45	mm
Initial Area	3375	sq mm
Area without closure after expansion	2527	sq mm
% of open cavity	**74.87**	%
% of closure	25.13	%

Area 2 (Front view)

	Values	Units
Initial length	29.46	mm
initial breadth	45	mm
Initial Area	1325.7	sq mm
Area without closure after expansion	733.59	sq mm
% of open cavity	**55.34**	%
% of closure	44.66	%

Area 2 (Front view)

	Values	Units
Initial length	5.9	mm
initial breadth	45	mm
Initial Area	265.5	sq mm
Area without closure after expansion	263	sq mm
% of open cavity	**99.06**	%
% of closure	0.94	%

Area 2 (Front view)

	Values	Units
Initial length	25.6	mm
initial breadth	45	mm
Initial Area	1152	sq mm
Area without closure after expansion	964	sq mm
% of open cavity	**83.68**	%
% of closure	16.32	%

Area 1 (Top view)

	Values	Units
Initial length	75	mm
initial breadth	45	mm
Initial Area	3375	sq mm
Area without closure after expansion	3363	sq mm
% of open cavity	**99.64**	%
% of closure	0.36	%

Area 1 (Top view)

	Values	Units
Initial length	75	mm
initial breadth	45	mm
Initial Area	3375	sq mm
Area without closure after expansion	3337	sq mm
% of open cavity	**98.87**	%
% of closure	1.13	%

Area 1 (Top view)

	Values	Units
Initial length	75	mm
initial breadth	45	mm
Initial Area	3375	sq mm
Area without closure after expansion	3307	sq mm
% of open cavity	**97.99**	%
% of closure	2.01	%

Area 2 (Top view)

	Values	Units
Initial length	28	mm
initial breadth	45	mm
Initial Area	1260	sq mm
Area without closure after expansion	624	sq mm
% of open cavity	**49.52**	%
% of closure	50.48	%

Area 2 (Top view)

	Values	Units
Initial length	31.2	mm
initial breadth	45	mm
Initial Area	1404	sq mm
Area without closure after expansion	1096	sq mm
% of open cavity	**78.06**	%
% of closure	21.94	%

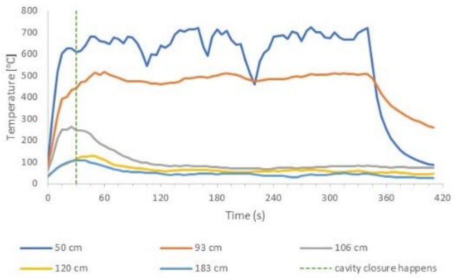
Area 2 (Top view)

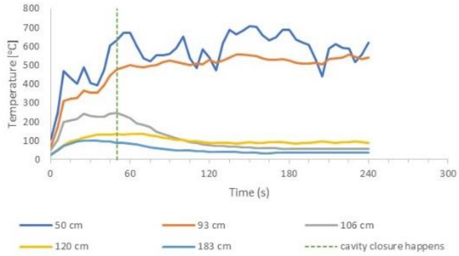
	Values	Units
Initial length	24.26	mm
initial breadth	45	mm
Initial Area	1091.7	sq mm
Area without closure after expansion	502	sq mm
% of open cavity	**45.98**	%
% of closure	54.02	%

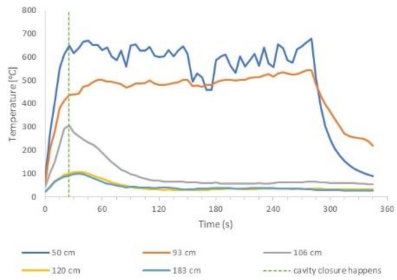
Table 7 Data's from the three set of tests for the Scenario 5

Test 1	**Test 2**	**Test 3**

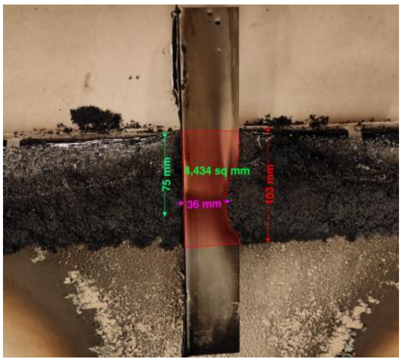
Thermocouple readings

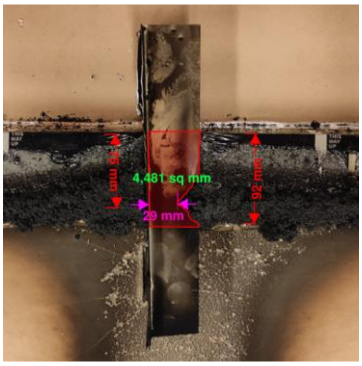


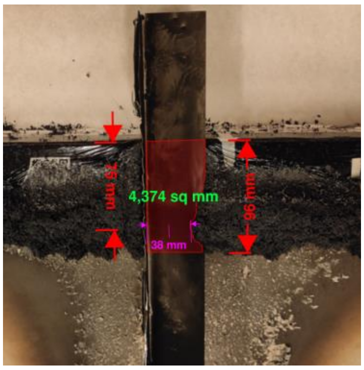


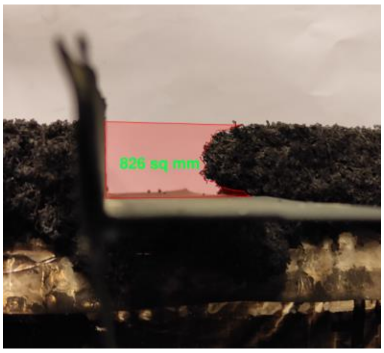


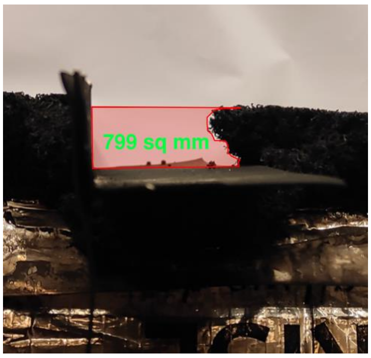
Images showing the area calculation by scaling the image using Bluebeam Revu software











Percentage of cavity closure calculated (Front View)

Area 1 (Front view)

	Values	Units
Initial length	103	mm
initial breadth	50	mm
Initial Area	5150	sq mm
Area without closure after expansion	4434	sq mm
% of open cavity	**86.10**	%
% of closure	13.90	%

Area 1 (Front view)

	Values	Units
Initial length	92	mm
initial breadth	50	mm
Initial Area	4600	sq mm
Area without closure after expansion	4481	sq mm
% of open cavity	**97.41**	%
% of closure	2.59	%

Area 1 (Front view)

	Values	Units
Initial length	96	mm
initial breadth	50	mm
Initial Area	4800	sq mm
Area without closure after expansion	4374	sq mm
% of open cavity	**91.13**	%
% of closure	8.88	%

<u>Percentage of cavity closure calculated (Top View)</u>

Area 1 (Top view)

	Values	Units
Initial length	25	mm
initial breadth	50	mm
Initial Area	1250	sq mm
Area without closure after expansion	826	sq mm
% of open cavity	**66.08**	%
% of closure	33.92	%

Area 1 (Top view)

	Values	Units
Initial length	25	mm
initial breadth	50	mm
Initial Area	1250	sq mm
Area without closure after expansion	829	sq mm
% of open cavity	**66.32**	%
% of closure	33.68	%

Area 1 (Top view)

	Values	Units
Initial length	25	mm
initial breadth	50	mm
Initial Area	1250	sq mm
Area without closure after expansion	799	sq mm
% of open cavity	**63.92**	%
% of closure	36.08	%

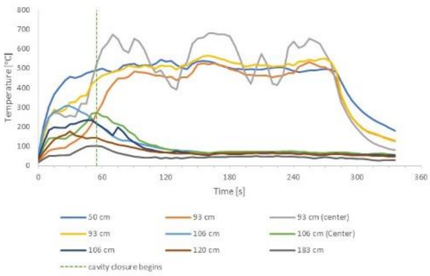
Table 8 Data's from the three set of tests for the Scenario 6

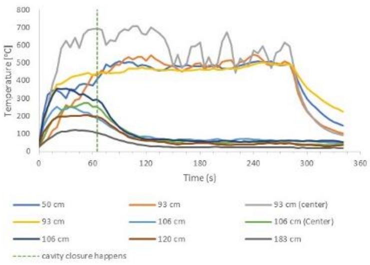
Test 1

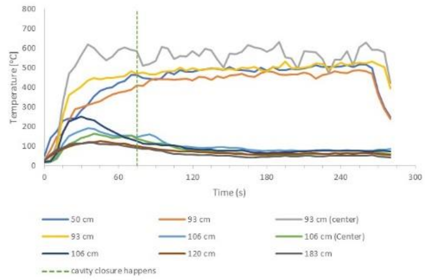
Test 2

Test 3

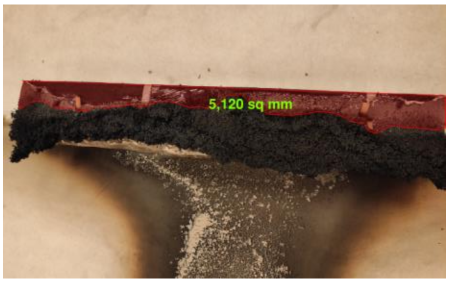
Thermocouple readings

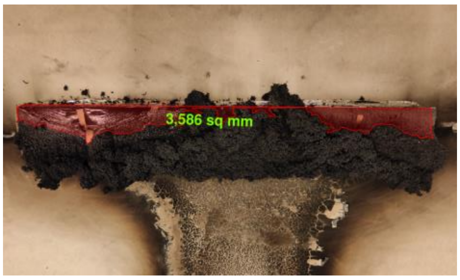


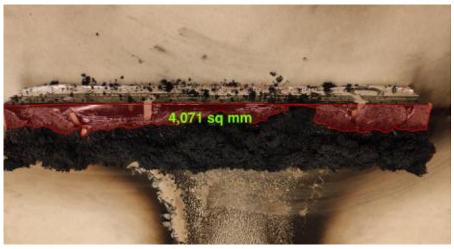




Images showing the area calculation by scaling the image using Bluebeam Revu software







Percentage of cavity closure calculated (Front View)

Area measurments		
	Values	**Units**
length	300	mm
breadth	75	mm
initial area	22500	sq mm
unexpanded area of intumescent strip	5120	sq mm
% of area not expanded	**22.76**	%
% of area expanded	77.24	%

Area measurments		
	Values	**Units**
length	300	mm
breadth	75	mm
initial area	22500	sq mm
unexpanded area of intumescent strip	3585	sq mm
% of area not expanded	**15.93**	%
% of area expanded	84.07	%

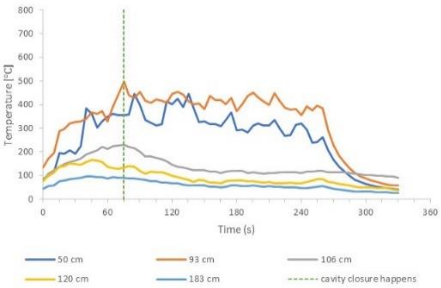
Area measurments		
	Values	**Units**
length	300	mm
breadth	75	mm
initial area	22500	sq mm
unexpanded area of intumescent strip	4070	sq mm
% of area not expanded	**18.09**	%
% of area expanded	81.91	%

Table 9 Data's from the three set of tests for the Scenario 7

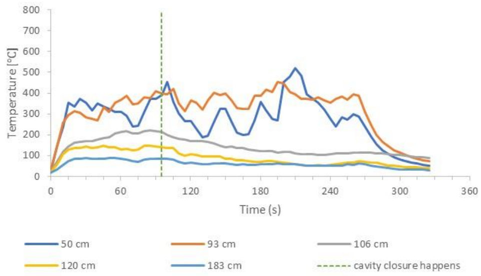
Test 1	**Test 2**	**Test 3**

Thermocouple readings

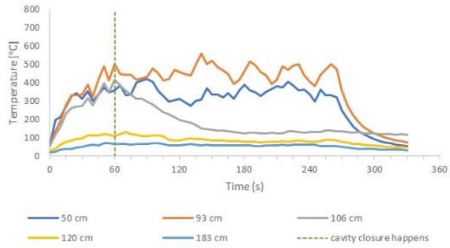
Test 1



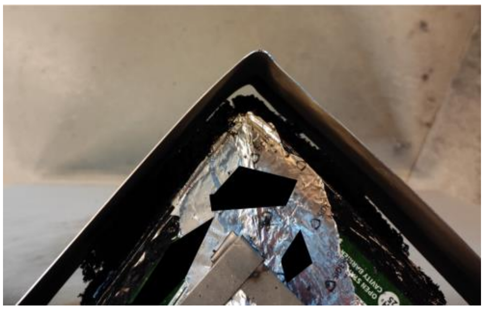
Test 2



Test 3



cavity closure photos (Top View)



Intumescent material expansion (Front View)

7 Discussion

The primary emphasis of this research lies in conducting a detailed comparison between Scenario 1, OSCB installed as per manufacturer guidelines, with other scenarios (Scenarios 2 to 7). The objective of this comparative analysis is to elucidate the consequences of deviations from the established guidelines on the propagation of fire and smoke to upper compartments. Additionally, this examination will be compared with the qualitative analysis conducted by David Comiskey et al. [19] regarding the installation of cavity barriers.

A comprehensive examination is made in comparison between Scenario 1 with Scenarios 2, 3, and 4. As elaborated in the section 5.3. The scenarios 2, 3 and 4 are the test done by keeping the gap between the OSCB blocks, at intervals of 15 mm, 30 mm, and 45 mm respectively. The aim is to discern how the increase in gap sizes between the OSCB blocks impact the cavity closure and preventing the smoke and flame propagation to the upper compartment during a fire incident.

Furthermore, Scenario 5, Cavity barrier installed with a blockage in front of intumescent material, contributes to the investigation by identifying the effects of blockages in front of the cavity barriers. This scenario will be analysed in conjunction with the benchmark, Scenario 1, providing insights into the role of blockages in influencing the compartmentation.

Expanding the scope of research, Scenario 6 introduces an OSCB installation featuring a cavity that is 50% larger than the OSCB product can be applicable. This particular scenario allows us to explore the implications of a large cavities that are more than the maximum limit of the OSCB and to understand its efficiency in closing the cavity during a fire incident.

Scenario 7, which provides the details how the cavity barrier will perform at corners and its efficacy in closing the cavity at corners in faulty installation methods will be analysed mainly through visual images and the thermocouple readings, As the Scenario 1 has completely different installation setup that has been followed, a comparative analysis of Scenario 7 with Scenario 1 is not practically possible.

7.1 Scenario 1 – Experiment with OSCB installed as per Manufacturer Guidelines

The expansion of the intumescent strip positioned in front of the cavity barrier commenced approximately 17 seconds after the temperature reading for the thermocouple just below the cavity barrier (93 cm as indicated in the Figure 46) surpassed 500 °C. The expansion of intumescent strip was found to be completed by 75 seconds. The beginning and completion of expansion of the intumescent strip in front of the OSCB are marked in the Figure 79. These values are substantiated by videography evidence from the experiment and the observation of the temperature of the thermocouple just above the cavity barrier (at a height of 106 cm from the base of propane burner). This thermocouple reading shows a dropdown in temperature at the point where the cavity begins to close due to the expansion of intumescent strip and after certain time, the temperature become study as indicated in Figure 79.

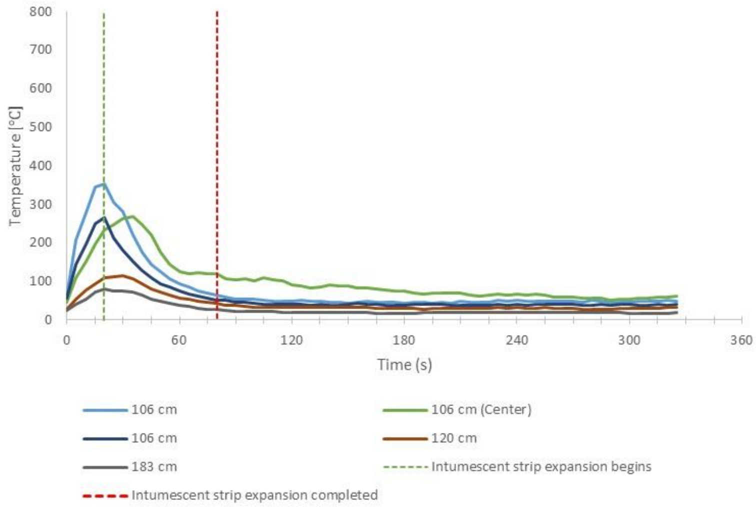


Figure 79 - Beginning and completion of expansion of the intumescent strip in front of the OSCB

During the course of the experiment, it was observed that the temperature reading of the thermocouple placed just above the cavity barrier dropped below 200 °C by 40 seconds. This occurrence signifies a significant cooling effect within the specified timeframe. Furthermore, the temperature was dropped down below 100 °C within a time of 75 seconds.

While evaluating the area of closure, denoted as “Area 1” in the corresponding section 5.2.3, it was determined that the percentage of the intumescent strip that did not expand ranged from 23 to 27%. This analysis was conducted at a point in time when the cavity was conclusively found to be fully closed. Consequently, the OSCB demonstrated an effective closure mechanism, successfully sealing the cavity within a duration of 80 seconds after the initiation of the fire.

7.2 Scenario 2, 3, and 4 – Experiment with OSCB installed with a gap in between the OSCB blocks

Scenarios 2, 3, and 4 investigate the impact of varying gaps between two OSCB blocks as discussed in section 5.3. Scenario 1, 2 and 3 are with a 15 mm, 30 mm and 45 mm gaps in between the OSCB blocks respectively. From the Figure 80, it is visible that for the Scenario 2, the cavity closure begins by a time of 37 seconds and completes within 75 seconds. However, while comparing the closure time with the Scenario 1, it was noticed that there is a bit delay. However, the time of closure is much more for the Scenario 4 where the beginning of intumescent strip expansion and completion was noted as 40 seconds and 130 seconds respectively. As mentioned in the
Table 10, the Scenario 2 and 3 resembles similar beginning and ending time for the intumescent strip expansion.

While analysing the graphs depicted in Figure 80, Figure 81, and Figure 82 for the Scenario 2, 3 and 4 respectively, it was identified that the temperature for the thermocouple kept just above the gap (at 106 cm from the base of the propane burner) was not getting reduced below 100 °C as found in the Scenario 1. Instead, there were fluctuations happening throughout and an average temperature shown was 200 °C, 250 °C, and 240 °C for the Scenario 2, 3 and 4 respectively as indicated in the

Table 10. It was noticeable that the temperature reading at zone 2 of the experiment at a height of 183 cm from the base of the propane burner was showing a higher temperature of 180 °C and 200 °C for the scenario 3 and 4 respectively, where it was below 100 °C for the Scenario 1 and 2.

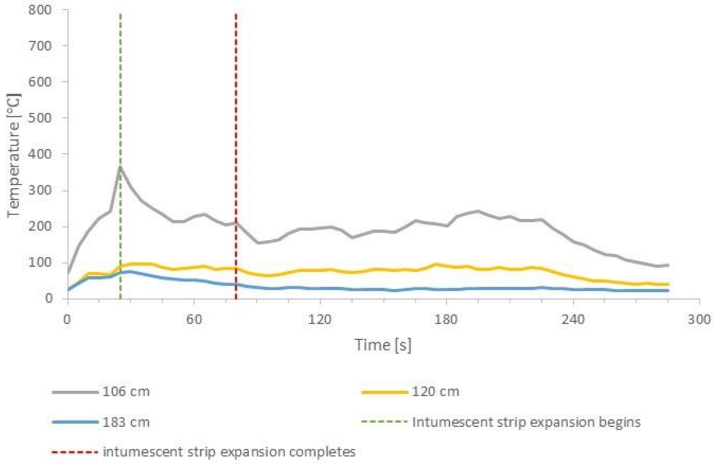


Figure 80 - Beginning and ending of the intumescent strip expansion for zone 2 of the Scenario 2, with 15 mm gap.

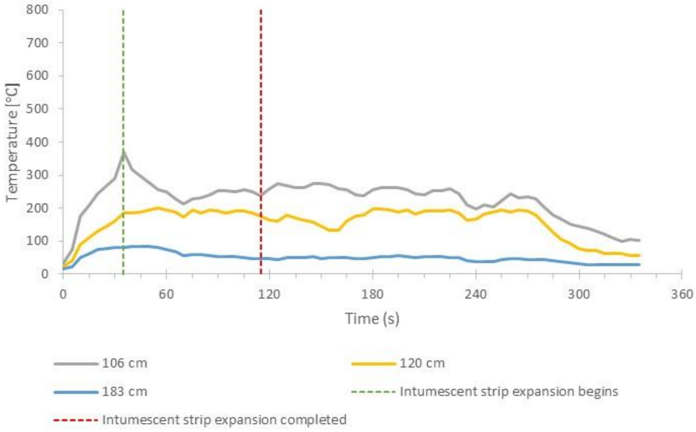


Figure 81 - Beginning and ending of the intumescent strip expansion for zone 2 of the Scenario 3, with 30 mm gap.

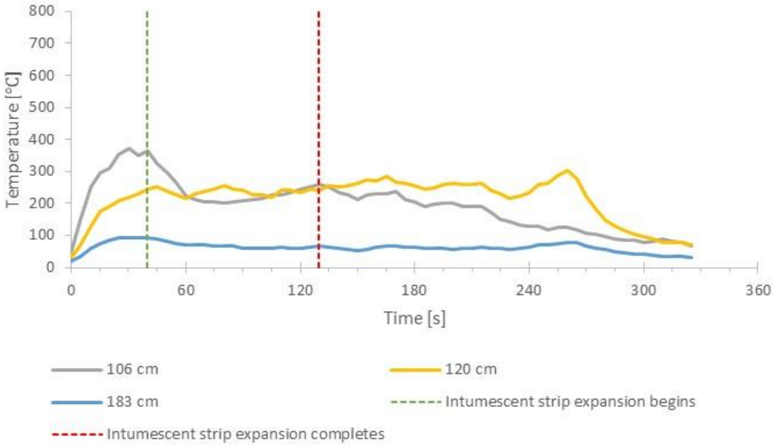


Figure 82 - Beginning and ending of the intumescent strip expansion for zone 2 of the Scenario 4, with 45 mm gap.

Table 10 Comparison of the temperature at zone 2 and cavity closure time for different scenarios

Scenario	Time of intumescent strip expansion (s)		Temperature reading of thermocouple placed at 106 cm height from the base of propane burner (°C)		Temperature reading of thermocouple placed at 120 cm height from the base of propane burner (°C)	
	Begins	Ends	Avg. value Before expansion	Avg. value After expansion	Avg. value Before expansion	Avg. value After expansion
1 (No gap)	17	75	360	80	110	80
2 (15 mm gap)	27	80	370	200	100	80
3 (30 mm gap)	35	115	385	250	190	180
4 (45 mm gap)	40	130	390	240	230	240

While considering the area of expansion of the intumescent strip, Area 1, which remained unclosed by the intumescent strip in front of the cavity barrier, constituted around 45% for both Scenarios 2 and 3. However, in Scenario 4, the cavity remained open up to 75%, attributed to the flame taking out the expanded intumescent strip in those locations. Despite these variations, there were no considerable changes in the gap between the two cavity barriers (top view) for all three experiments. The gap between the mineral wool part of the OSCB (Area 2) remained consistent, with no intumescent material bending towards the gap. Consequently, the measured area for this remained unclosed at 90 – 95%. This fact is crucial as it contributes to the dominant visibility of flames in Zone 2 for Scenario 4 throughout the experiment, whereas no flames were observed in Zone 2 for Scenario 2.

Upon analysing the results using the FMEA analysis conducted by David Comiskey et al.[19]and referencing Table 1 and Table 2, a high-risk level was initially assigned. However, it was observed that, despite the high overall risk, the risk level for all gaps was not deemed critical. A detailed examination of values, encompassing temperature in Zone 2 and the extent of flame penetration through the gap, revealed that a cavity size of up to 15 mm was deemed acceptable with minimal risk of fire spreading to the upper compartment.

Nevertheless, as the cavity size increased to 30 mm, the fire became more dominant, and the temperature exceeded 200 °C. The risk was categorized as very high for the 45 mm gap. Consequently, the risk levels can be classified as follows:

- For a 15 mm gap between cavity barriers: Low;
- For a 30 mm gap between OSCB blocks: Medium;
- For a 45 mm gap between OSCB blocks: High.

7.3 Scenario 5 - Experiment with a blockage in front of OSCB.

Scenario 5 involved the introduction of a blockage in front of the intumescent strip, aiming to gain insights into the expansion and closure of the cavity during a fire. The time of beginning of the expansion of intumescent strip for the Scenario 5 was observed same as that of Scenario 1, occurring within a range of 25 to 30 seconds. However, the completion of the expansion of intumescent strip was found to happen after 110 seconds which was much more than that of Scenario 1 as indicated in the Figure 83.

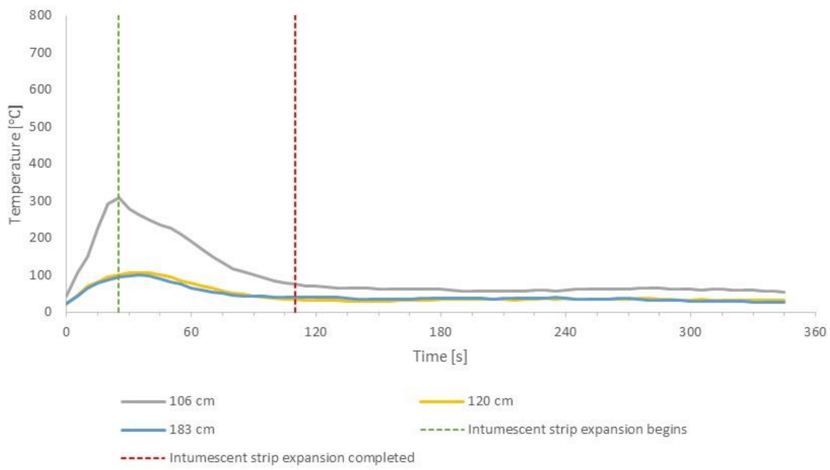


Figure 83- Beginning and ending of the intumescent strip expansion for zone 2 of the Scenario 5.

The temperature of the thermocouple just above the OSCB (at a height of 106 cm from the bottom of propane burner) was found to be 310 °C at which the expansion of the intumescent strip begins. The temperature was found to get dropped to 85 °C which was almost similar to that of the Scenario 1 as indicated in the Table 11. Moreover, the temperature reading of the thermocouple placed at a height of 120 cm from the bottom of the propane burner also shown the same dropdown for the Scenario 5 while compared with the scenario 1.

Table 11 Comparison of the temperature at zone 2 and cavity closure time for scenarios 1 and 5.

Scenario	**Time of intumescent strip expansion (s)**		**Temperature reading of thermocouple placed at 106 cm height from the base of propane burner (°C)**		**Temperature reading of thermocouple placed at 120 cm height from the base of propane burner (°C)**	
	Begins	**Ends**	**Avg. value Before expansion**	**Avg. value After expansion**	**Avg. value Before expansion**	**Avg. value After expansion**
1 (No gap)	17	75	360	80	110	80
5 (with Blockage)	26	110	310	85	100	70

Upon examining the area of closure for the intumescent strip, it was noted that no intumescent material covered the cavity created by the blockage as indicated in the Figure 70 (b). It was noted that the expanded intumescent material was carried away by hot plumes and flames which makes the closure of cavity difficult. Approximately 90% of the cavity was found to be remained unfilled, revealing a substantial lack of closure when considering Area 1, as detailed in the sections 6.1.2.

These findings underscore the distinctive behaviour introduced by the blockage in front of the intumescent strip, influencing both the temperature at the zone 2 and the closure effectiveness of the cavity barrier.

However, considering the inadequate closure of the cavity resulted from the obstruction of the specified size in the given scenario, the risk level was categorized as medium, as the likelihood of this scenario occurring was predominantly identified through on-site inspections.

7.4 Scenario 6 - OSCB installed with a 50% larger cavity gap than the allowable cavity.

Scenario 6 presented a condition with a 50% larger cavity in front of the intumescent strip of the OSCB than the allowable value. While analysing the thermocouple values, the temperature recorded for the thermocouple just above the cavity barrier (106 cm from the bottom of propane burner) initially reached approximately 350 °C. As the intumescent strip started expanding, the temperature gradually decreased, reaching around 100 °C by taking around 120 seconds. However, it was noted that the temperature dropped below 200 °C by a time of 70 seconds as indicated in the Figure 84.

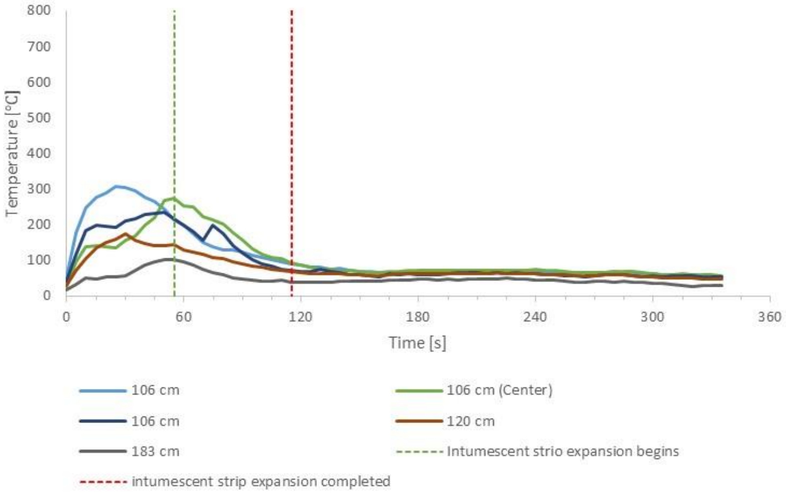


Figure 84 - Beginning and ending of the intumescent strip expansion for zone 2 of the Scenario 6.

Analysis of video graphic evidence revealed complete closure of the cavity area, with no flame present in Zone 2 after 110 seconds. The percentage of non-expanded intumescent strip for the cavity barrier was approximately 20%, in contrast to the 40% observed in Scenario 1. These values suggest that a larger portion of the intumescent material expanded while compared with the Scenario 1, as the cavity was increased by 50% beyond the allowed value as discussed in the section 5.5. However, the cavity was completely closed with a delayed time while comparing with the scenario 1 with a usage of around 8 to 12% of more intumescent material.

Table 12 Comparison of the temperature at zone 2 and cavity closure time for scenarios 1 and 6.

Scenario	**Time of intumescent strip expansion (s)**		**Temperature reading of thermocouple placed at 106 cm height from the base of propane burner (°C)**		**Percentage of intumescent material (%)**	
	Begins	**Ends**	**Avg. value Before expansion**	**Avg. value After expansion**	**Expanded**	**Not expanded**
1 (No gap)	17	75	360	80	72 - 77	23 - 27
6 (Extended cavity)	55	110	290	90	78 - 84	16 - 22

Nevertheless, despite the extended time taken for the closure of the cavity, which exceeded the duration for scenario 1, the risk level for this scenario was classified as low. The escalation of temperature and smoke in zone 2 was effectively managed following the complete expansion of the intumescent strip.

7.5 Scenario 7 - Experiment with OSCB at corners

Scenario 7 aimed to assess the effectiveness of cavity closure at corners by the OSCB during a fire incident. While analysing the thermocouple readings, the temperature recorded for the thermocouple just above the cavity barrier (at 106 cm from the bottom of the propane burner) peaked at 220 °C, decreasing to below 150 °C after 120 seconds.

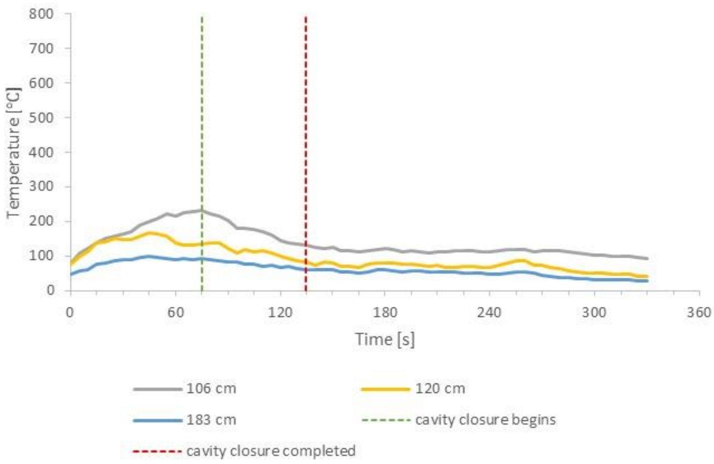


Figure 85 - Beginning and ending of the intumescent strip expansion for zone 2 of the Scenario 7.

Owing to the obstructed view from the side caused by the metal sheet used in constructing the corner structure, the entry of flames into Zone 2 was not visible. However, post-test cavity inspection revealed the incomplete closure of the cavity happened at the corners. This was attributed to a presumed lack of intumescent material in those areas. Further investigation is suggested to determine the optimal practices for corner installations and enhance strategies to minimize flame and smoke spread to upper compartments.

However, given the higher likelihood of occurrence with this installation method, the necessity of identifying a procedure ensuring proper cavity closure becomes highly pertinent. Following the identification of improper closure at the corners and a high probability of occurrence, the risk level is deemed to be within the medium range.

8 Conclusion

In conclusion, this research primarily focuses on a detailed comparison between Scenario 1, where OSCB is installed according to manufacturer guidelines, and other scenarios (Scenarios 2 to 7). The objective is to understand the impact of deviations from established guidelines on fire and smoke propagation to upper compartments. This analysis is further compared with the qualitative analysis conducted by David Comiskey et al. [19] concerning cavity barrier installations.

The examination begins with a comprehensive comparison between Scenario 1 and Scenarios 2, 3, and 4, where the gap between OSCB blocks is varied. The study reveals that an increase in gap size influences cavity closure efficiency, with larger gaps leading to higher risks of fire spread. The risk level can be classified as follows;

- For a 15 mm gap between cavity barriers: Low;
- For a 30 mm gap between OSCB blocks: Medium;
- For a 45 mm gap between OSCB blocks: High.

Scenario 5 introduces a blockage in front of the intumescent strip, highlighting challenges in cavity closure due to blockage-induced complications. Scenario 6 explores the implications of installing OSCB with a 50% larger cavity, demonstrating delayed closure with increased intumescent material usage. It was found that no critical temperature rise was happening in the zone 2 of the experimental setup. However, the presence of flame in the zone 2 was critical as the blockage allows the fire to penetrate to the upper compartment as the intumescent material was taken away by hot plume gas and thereby the cavity was not closing. This may lead to fire propagation to the upper compartment if there is any combustible materials installed in line with the blocking material.

Scenario 7 evaluates OSCB performance at corners, revealing incomplete closure and suggesting the need for further investigation into optimal installation practices. However, a practice that was identified from the site visit provides a potential improvement in the installation technique that may provide better cavity closure at corners.

The detailed analysis provides valuable insights into the efficiency of OSCB installations in various scenarios, contributing to the understanding of fire safety measures and highlighting areas that require further exploration and improvement.

9 Further exploration and improvement opportunities

Additional enhancements can be explored to enhance our understanding of cavity barrier efficiency, encompassing:

- Enhanced techniques for installing cavity barriers at corners, as detailed below:

During the site visits, it was noticed an alternate way of installation of cavity barriers at the corners without having any cut happening for the intumescent material as indicated in the Figure 86 and Figure 87. This installation method required more testing to understand the efficiency of cavity closure. However, as there is intumescent strip present for these at corners, the chance of proper closure is comparatively more than the traditional installation methods.

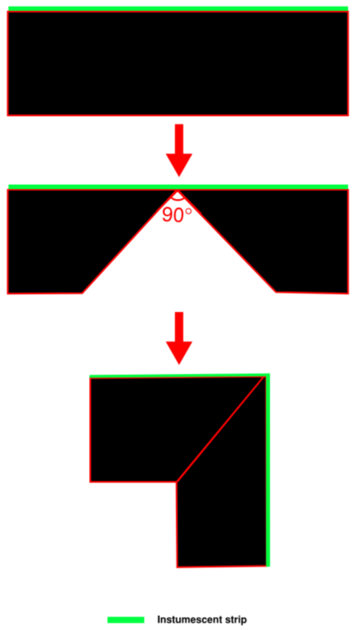


Figure 86 - Installation method that found during site which is not as per the manufacturer guidelines

Figure 87 - Deviation from the installation guidelines noticed for the corners

- Identification of flame spread in scenarios with real-time installation methods in Zone 2, considering the presence of combustible membranes typically installed on external walls.
- Investigation into cavity sizes beyond the 50% tested in Scenario 6, and determination of the minimum required thickness of intumescent strip to prevent fire spread to the upper compartment.
- The experimental duration was limited to 5 minutes, constraining the ability to comprehensively assess the long-term behaviour of the cavity barrier when subjected to fire in each scenario. Conducting experiments with extended durations would afford a more nuanced understanding of the cavity barrier's performance over prolonged exposure to fire in various scenarios.

Reference

[1] Yılmaz, D. G. (Year). Fire Safety of Tall Buildings: Approach in Design and Prevention. Bursa Technical University, Faculty of Architecture and Design, Bursa, Turkey.

[2] National Fire Protection Association. (2022). NFPA 285: Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components. National Fire Protection Association. https://www.nfpa.org/codes-and-standards/2/8/5/nfpa-285

[3] BS 8414 Fire performance of external cladding systems. Retrieved from https://www.designingbuildings.co.uk/wiki/BS_8414_Fire_performance_of_external_cladding_systems

[4] Australian Building Codes Board. (2023). National Construction Code. Retrieved from https://ncc.abcb.gov.au/

[5] Song, L., Zhu, J., Liu, S., & Qu, Z. (2022). Recent Fire Safety Design of High-Rise Buildings. College of Civil Engineering and Architecture, Harbin University of Science and Technology, 150080 Harbin, China.

[6] Lane, B. (2018). Grenfell Tower - Fire Safety Investigation Phase 1 Report - Section 11: Construction of the External Walls - The Provisions Made at Grenfell Tower to Comply with Building Regulations. Retrieved from https://www.grenfelltowerinquiry.org.uk/evidence/dr-barbara-lanes-expert-reportSFPE. (Fifth Edition.). (2016). SFPE Handbook of Fire Protection Engineering (5th ed.). Springer. Vol1.

[7] British Standards Institution. (2022). PAS 9980:2022 Fire Risk Appraisal of External Wall Construction and Cladding of Existing Blocks of Flats – Code of Practice. BSI Standards Limited.

[8] UK Government. (2021, January). Research and analysis Building Safety Programme: Waking Watch costs, Jan 2021. Retrieved from https://www.gov.uk/government/publications/building-safety-programme-waking-watch-costs/building-safety-programme-waking-watch-costs

[9] Shipp, M., Holland, C., Crowder, D., & Lennon, T. (2015). *Fire Compartmentation in Roof Voids*. Watford: BRE.

[10] Daly, M., Comiskey, D., & Millar, R. (2019). Using Technology as a Means of Verifying the Positioning of Cavity Barriers in a Building Wall Envelope. In A. Hore, B. McAuley, & R. West (Eds.), CitA BIM Gathering 2019, September 26, Galway, Ireland. Construction IT Alliance, 16-22.

[11] Littlewood, J. R., Alam, M., Goodhew, S., & Davies, G. (2017). The Safety Gap in Buildings: Perceptions of Welsh Fire Safety Professionals. *Energy Procedia, 134*(1), 787-798.

[12] Littlewood, J. R., & Smallwood, I. (2017). In-construction tests show rapid smoke spread across dwellings. *Engineering Sustainability, 170*(2), 102-112.

[13] Building Safety Programme. (n.d.). Waking Watch Costs. Retrieved from https://www.gov.uk/government/publications/building-safety-programme-waking-watch-costs/building-safety-programme-waking-watch-costs

[14]Welsh Government. (2015). Approved Document B, Volume 2, Buildings Other Than Dwelling Houses (2006 Edition Incorporating 2010, 2013 and 2016 Amendments) (for Use in Wales). Retrieved from https://tinyurl.com/y887643s

[15]Bisby, L. (2018). Grenfell Tower Inquiry Phase 1 - Expert Report. Retrieved from https://tinyurl.com/yc6ogjjw [Accessed July 11, 2020].

[16]Anderson, J., Boström, L., Chiva, R., et al. (2021). European approach to assess the fire performance of façades. Fire and Materials, 45, 598–608. https://doi.org/10.1002/fam.2878

[17]HM Government. (2013). Approved Document 7, Materials and Workmanship. Retrieved from https://tinyurl.com/y8c6zbct

[18]Vivalda. Siderise cavity barriers. Retrieved from https://www.vivalda.co.uk/products/frame-fixings/cavity-fire-barriers-siderise/

[19]Comiskey, D., & Wilson, K. (2020). A Performance Barrier? Cavity Barrier Installation in Wall Envelope Makeups. In L. Scott & C. J. Neilson (Eds.), Proceedings of the 36th Annual ARCOM Conference, 7-8 September 2020, UK (pp. 205-214). Association of Researchers in Construction Management.

[20]Hackitt, J. (2017). Building a Safer Future, Independent Review of the Building Regulations and Fire Safety: Interim Report. London: HMSO. Available from https://tinyurl.com/y7lo3x3t

[21]Comiskey, D., Hyde, T., Millar, P., & O'Kane, E. (2019). The Quality Dimension (qD). In A. Hore, B. McAuley, & R. West (Eds.), *CitA BIM Gathering 2019*, 26 September, Galway, Ireland. Construction IT Alliance, 160-168.

[22]Comiskey, D., Stubbs, R., Luo, X., Hyde, T., & O'Kane, E. (2018). The devil is in the detail: The link between building regulatory processes, on-site inspection, verification, and technology. In *2nd International Symposium on Small-Scale Intelligent Manufacturing Systems*, 16-18 April 2018, Cavan, Ireland.

[23] Daly, M., Comiskey, D., & Millar, R. (2019). Using Technology as a Means of Verifying the Positioning of Cavity Barriers in a Building Wall Envelope. In A. Hore, B. McAuley, & R. West (Eds.), *CitA BIM Gathering 2019*, 26 September, Galway, Ireland. Construction IT Alliance, 16-22.

[24]City of Edinburgh Council. (2017). *Report of the Independent Inquiry into the Construction of Edinburgh Schools*. Available from https://tinyurl.com/y5777bby

[25]Dumfries and Galloway Council. (2018). *Report of the Independent Inquiry into the Construction of the DG One Complex in Dumfries*. Available from https://dumgal.gov.uk/article/17432/DG-One-build-inquiry.

[26]Department for Communities and Local Government (DCLG). (Year, if available). Title of the Specific Document or Publication. Retrieved from https://www.gov.uk/government/organisations/ministry-of-housing-communities-and-local-government

[27]Siderise Open State Cavity Barriers, https://www.siderise.com/products/facades/open-state-cavity-barriers

[28]Requirements for Cavity Barriers to Concealed Spaces Located Behind Cladding with Masonry Substrates to Houses and Flats. (April 2022). Technical Guidance 6.1/34.

[29]ASFP Technical Guidance Document - TGD 19, Fire Resistance Test for 'Open-State' Cavity Barriers used in the external envelope or fabric of buildings, https://assets.grenfelltowerinquiry.org.uk/

[30]Sharma, A., & Mishra, K. B. (2021). Experimental investigations on the influence of 'chimney-effect' on fire response of rainscreen façades in high-rise buildings. Journal of Building Engineering, 44, 103257. https://doi.org/10.1016/j.jobe.2021.103257