出國報告（出國類別：國際會議）

參加第 12 屆性能法規與防火設計方法國際研討會

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派赴國家：美國
出國期間：**107** 年 **4** 月 **22** 日至 **28** 日
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摘　　要

關鍵詞：防火安全、防火性能法規、國際研討會

第 12 屆性能法規與防火設計方法國際研討會（The SFPE 12th International Performance-Based Codes and Fire Safety Design Methods）係由美國防火工程師協會（The Society of Fire Protection Engineers，SFPE）每兩年舉辦一次國際研討會，整個活動包括Poster Session、消防避難產業設施展覽及參加性能法規與防火設計方法國際研討會，研討內容包括大空間火災模擬實驗、CFD模擬、隧道火災特徵、建築外牆防火性能與危害分析、CLT高層木構造防火與個案分析、綠屋頂與防火、性能式設計的工具與應用、或然性分析法、個案分析、等內容。我國業施行建築防火性能法規及設計評定審查十餘年，藉由參與國際研討會，蒐集建築防火研究及實驗相關研究成果，可供本所對於建築防火工程技術、木構造防火及性能式設計的研究領域有所拓展與啟發，並做為本所相關科技計畫內容與研究課題之研擬、修訂參考，同時積極參與國際研討交流平台汲取國外創新技術，有利國內法規制度及設計技術之提升。

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壹、目的

我國業施行建築防火性能法規及設計評定審查十餘年，藉由參與國際研討交流平台汲取國外創新技術，有利國內法規制度及設計技術之提升，本研討會由美國防火工程師協會每兩年舉辦防火性能法規及設計法相關國際研討會，提供各先進國家專家最新建築物防火研究及設計案例研討，本次活動包括，參加 Poster Session、消防避難產業設施展覽及相關會議資料蒐集–本學術海報討論內容包括避難逃生、消防系統設計安裝設計考量與成本分析、馬來西亞防火工業透視、特定建築使用耐火鋼技術評估設計、鐵路場站防火與人員安全、建築興建過程火災的防護等專題，現場除進行資料蒐集外，並可與發表者就內容進行研討；現場另有消防滅火設備、系統工程、避難逃生相關產業設施展覽，作為研討會實驗、理論內容與工程實務結合參考。另一個為參加性能法規與防火設計方法國際研討會，研討內容包括大空間火災模擬實驗、CFD 模擬、隧道火災特徵、建築外牆防火性能與危害分析、CLT 高層木構造防火、綠屋頂與防火、性能式設計的工具與應用、或然率分析法與個案分析等內容。

藉由參與國際研討交流平台汲取國外創新技術，有利國內法規制度及設計技術之提升，同時對國內已施行之建築防火性能法規及設計評定審查作業之精進參考。另外 瞭解 國際間對於性能式設計與應用、數值分析模擬工具的應用、CLT高層木構造之材料性質與防火及綠屋頂與防火之考量等最新研究成果，可供本所依據本部中程施政計畫施政綱要「建構永續、宜居環境」的目標下，據以 規劃後續科技計畫研擬 內容 之參考。

貳、過程

本次出國計畫係為參加第12屆性能法規與防火設計方法國際研討會及其相關海報論文、消防產業展覽等活動，出國時間為107年4月22日至4月28日共計7天，會議地點為美國夏威夷檀香山市，行程安排如表1所示。本次活動主辦單位為美國防火工程師協會（SFPE），贊助及展出單位共有6家相關產業單位。

表 1、本次出國計畫行程表

日期	活動內容	備註
4 月 22 日(日)	前往美國夏威夷州檀香山	路程
4 月 23、24 日(一、二)	參加 Poster Session、消防避難產業設施展覽及相關會議資料蒐集– 本學術海報討論內容包括避難逃生、消防系統設計安裝設計考量與成本分析、馬來西亞防火工業透視、特定建築使用耐火鋼技術評估設計、鐵路場站防火與人員安全、建築興建過程火災的防護等專題，現場除進行資料蒐集外，並可與發表者就內容進行研討。現場另有消防滅火設備、系統工程、避難逃生相關產業設施展覽，作為研討會實驗、理論內容與工程實務結合參考。	
4 月 25 日(三)	參加研討會，研討內容包括大空間火災模擬實驗、隧道火災特徵、建築外牆防火性能與危害分析、性能式設計的應用、或然性分析法以及個案分析等。	
4 月 26 日(四)	參加研討會，研討內容包括高層建築防火安全、建築法令、結構與防火、人員安全、CFD 模擬、防火系統、性能式設計工具以及 CLT 高層木構造個案分析等。	
4 月 27 日	參加研討會，研討內容包括 CLT 高層木構造個案分析、木	

(五)	材工程與防火、綠屋頂與防火及分析工具等。	
4 月 28 日 (六)	從美國夏威夷州檀香山返回台灣	路程

一、參加 Poster Session、消防避難產業設施展覽及相關會議資料蒐集

整個活動包括研討會會議地點為美國夏威夷檀香山市的希爾頓夏威夷度假酒店，相關海報發表會議(Poster Session)及消防避難產業設施展覽於會議休息區進行展出，部分海報作者會於特定時段到場介紹說明並與參加者進行問題研討，會場提供大量的桌椅，可供與會者有很輕鬆的空間進行詳細的討論交流。

圖 1、會議舉辦地點

圖 2、會議報到處

圖 3、會議手冊

圖 4、報到處展出的 SFPE 出版品

圖 5、海報發表會議及消防避難產業設施展覽場地

海報發表會議4篇內容(如附錄1)分別摘要說明如下:

篇名	作者	摘要說明
Roadmap for Incorporation of Risk Criteria and Analysis in Building Regulatory Decisions	B.J. Meacham IJ.J. van Straalen	近年來，建築監管體系一直在演變，首先是向功能或性能式轉換，最近又引入了新的社會目標，包括與永續性和氣候變遷相關的目標。這一演變過程發現了各種政策和技術挑戰，包括缺乏一些共同基礎，如建立預期績效、量化績效衡量標準和強有力的機制納入新目標，以有效整合各種利益相關者意見和監管結果的方式不符合長期目標的要求。進化的管理機制之一是使用風險作為性能式的基礎，並

		在建築監管體系中進行修改以實現此目的。近期認為將建築監管體系框定為社會技術體系（STS）將突出監管機構與市場之間存在的複雜相互作用，利益相關方在建築監管中使用風險的特徵方面所扮演的角色，以及需要採取哪些步驟轉向基於風險的性能式建築監管體系，同時考慮到不同司法管轄區之間存在的不同法律結構和監管方法。
A cost benefit tool to analyse sprinklers as an option in the design of buildings	Anna Martensson Matilda Bjalkefur	本篇主要發展評估模式，評估安裝自動撒水設備的成本效益分析，包括在建築過程，如安裝自動撒水設備，可減少逃生梯數量，使用較低等級防火材料及防火設備(如無阻熱防火門窗)，可加大防火區劃等降低成本，但增加撒水系統費用；在營運過程，前開部分設施如逃生梯會佔用可出租空間，減少收入，如增加撒水系統可提高出租空間，增加收入，但增加撒水系統的維護費。本文案例經評估模式總結安裝撒水設備可有較佳的經濟效益。
Evaluation of the Fire Resistance for Simple Beams Built with TMC Fire Resistant Steels Using Fire Engineering Techniques	In-Kyu Kwon	本文探討用防火工程技術評估TMC耐火鋼建造的簡易樑抗火性能，其變數有: 鋼材種類、邊界條件和試件長度，分析方法除了高溫力學和熱性質，也包括熱和熱應力分析，探討包括力學/比熱性質、不同溫度下的變形量值、不同溫度下的最大荷重值。其結論有:

		1. 變形量在650度之前，TMC FR490有較佳的性能，但超過 650 度, 其變形量快速增加。 2. 最大承載力在 400 度之前，TMC FR490 有較佳的性能，但超過 400 度，其承載力下降，且略低於 FR490 鋼。 3. 鋼梁長度增加，最大承載力快速下降; 因此經標準試驗(標準尺度)獲得的耐火性能，不能確保用於其他尺度時的性能，所以建議不同尺寸應個案試驗或進行分析。
Design and Approval of a 60M Green Wall in an Internal Office Atrium	Nate Lobel Chris Chennel	綠色植生牆壁越來越受歡迎，但其安全性受到質疑，不僅僅需要經過防火測試，也要確保符合適當的政策和法規。本案例植生綠牆系統可使用至 60 米高，450 平方公尺面積(約 13500 盆植物) ，含水量 30%(體積比)，包覆聚胺脂發泡板，綠牆系統內含撒水系統。整個系統考量整體防火安全設計，設有偵煙設備和排煙系統，灌溉系統可延長避難時間，平時使用環境應降低引火源存在，牆上無高發熱照明系統等，以維安全。目前對綠色植生牆的安全設計，因其燃燒行為資訊少(HRR 和擴散速率)但其火載量大及擴散面積大，因此多數設計仍採保守設定。

圖6、海報發表作者 **Nate Lobel**

圖7、與**Nate Lobel**討論交流後合影

圖8、 綠色植生牆單元正面

圖9、綠色植生牆單元側面

海報發表中的綠色植生牆案例，與近來國內綠建築環境(包括綠屋頂及綠牆)以及外牆火災等研究上有相關，補充說明與簡報者討論及資料蒐集後的部分心得。

地球人口持續增加，且往都市集中生活，如此高度人口擁擠都市化的建築，往往朝高層建築發展，造成都市環境綠化最大的挑戰是空間的不足，因此垂直綠化做為內部或外部立面或屋頂綠化成了替代方法的一種，這種綠化植栽同時具有隔熱效果，也能有效降低都市高溫，形成節能綠環境的一環。

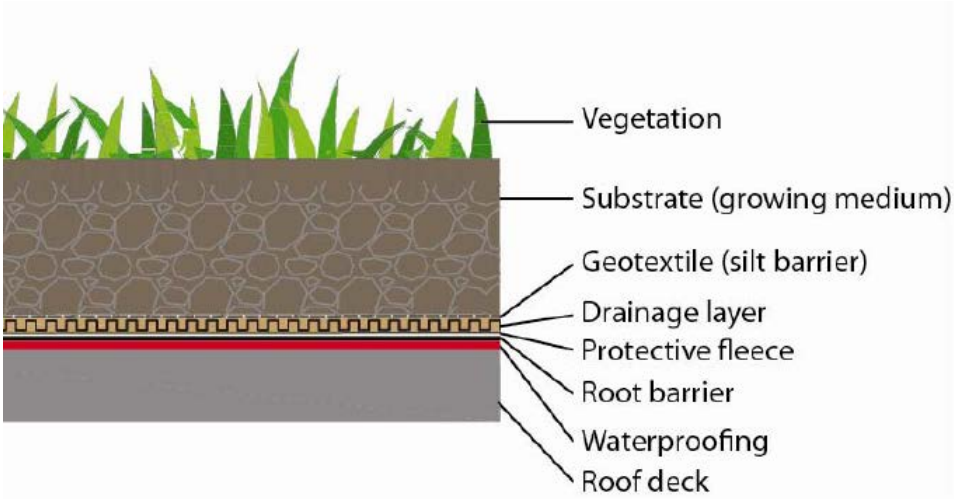


圖10、典型綠屋頂植栽系統斷面圖
(資料來源: Fire Performance of Green Roofs and Walls，Department for Communities and Local Government，UK，August 2013)

圖11、綠屋頂
(資料來源: Reaction to fire of Green Facades and Roofs，Nataša Knez, BRI/ENBRI Workshop, Brusseis, 12th Nov. 2014)

圖12、綠植栽牆
(資料來源: Fire Performance of Green Roofs and Walls，Department for Communities and Local Government，UK，August 2013)

但這種新型態的綠植生牆/綠屋頂防火安全仍有些疑慮，包括在建築法規上、安全設計、使用維護及相對應的測試標準等要求。對於這類新型物件的防火考量，簡要整理如下。

(一) 火災預防

•增加生長培養基的不可燃含量

•降低生長培養基的有機含量

•降低植栽框架系統材料的可燃性

•防止植生系統乾燥

部分地區綠屋頂規範規定，植物培養基層深度應大於 30mm，有機物含量不應超過 20％，而 ANSI 指南則規定生長介質必須含有至少 80％的無機物質。也建議種植多汁植物，因為它們將水保留在其結構中，可以降低了培養基變乾的風險。建議限制播種種類，以使植被的全長高度不超過 0.9 公尺。應該避免使用草和苔蘚，而應該使用耐火植物，例如具有高水分/低樹脂含量的植物。

粗放型(extensive)綠屋頂通常沒有灌溉，因此通過減少有機物含量以及規定建築物和防火間隔來減輕火災風險。對於經致型(intensive)而言，規範指定採“加強綠化、灌溉、定期維護並需具有一定厚度的基層”作為“硬頂”，以降低火災風險。

(二) 設置防火阻隔帶

如同建築防火區劃要求，許多的指導文件要求在達特定面積大小時提供非植物邊界區域以中斷火災擴散，火災中斷通常由非植物帶組成，例如維護通道。

(三)使用管理

設計、維護管理及生長良好的綠屋頂/牆，其火災風險其實是不高的，但使用管理上要注意維持灌溉系統的運作可靠度、避免植物乾枯、適時清除死掉或已乾枯的植物(枯葉枯枝)、植栽系統週遭勿有高發熱器具(如探照燈)長期照射以及設置適當的消防安全設備。

消防避難產業設施展覽單位共有Auto Sprink、Coffman Engineers、Peerless Pumps、Springer Nature及 Tornatech International Inc. 現場攤位展出內容如圖所示。現場展示多為書面介紹技術資料，內容包括各種消防泵(含配件)以及系統的規劃、設計、製造和安裝，另外包括系統週遭驅動器、控制器等；綜整未來發展趨勢包括在系統設計運用建築空間資訊，採智慧化設計，搭配整合設計、計算、物件座標等三維空間設計軟體，以使撒水滅火系統管路具有適當高程和坡度並按照業者現場安裝需求繪製系統，後續此設計模型資訊可轉作維護管理使用，以節省成本及提高效率。另外在維護管理方面，多採用圖形化、智慧化以及雲端化管理系統，以進行操作、監控和故障或甚至事故的通報、損管等處理。

圖13、Peerless Pumps 展覽文宣

圖14、Peerless Pumps 雲端無線操作監控系統示意圖

圖15、Coffman Engineers 展覽文宣

圖16、 Tornatech International Inc.展覽區

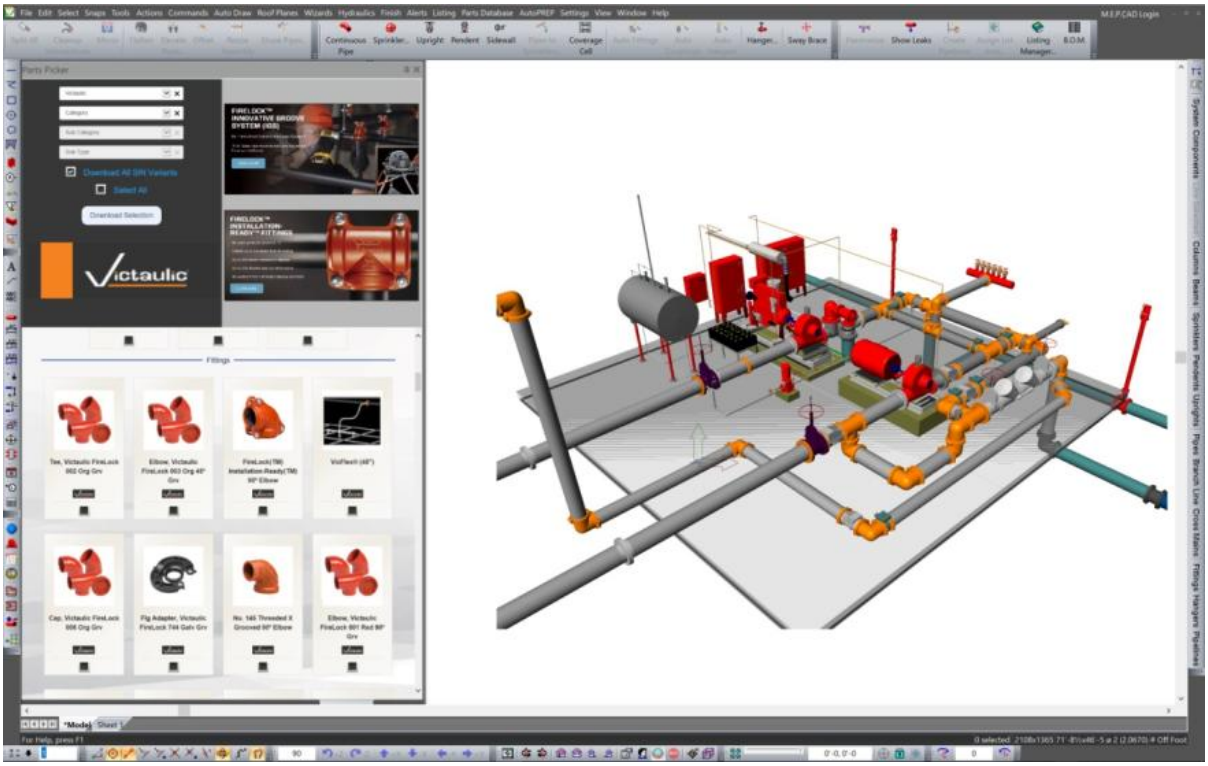


圖 17、 **AutoSPRINK** 系統設計資料庫示意圖

圖 18、 **Springer** 出版品展覽

二、第 12 屆性能法規與防火設計方法國際研討會

本次研討會內容包括大空間火災模擬實驗、隧道火災特徵、建築外牆防火性能與危害分析、性能式設計的應用、或然性分析法、高層建築防火安全、建築法令、結構與防火、人員安全、CFD模擬、防火系統、性能式設計工具、CLT高層木構造、木材工程與防火、綠屋頂與防火及分析工具等。研討內容相當豐富且時間緊湊，因此研討會分成A、B兩場地同時進行，會場內擺設如同宴會的圓桌(圖19)，參加者採開放式自由入席，可增進參加者互動討論的方便性。

圖19、研討會會場

圖20、研討會現場留影

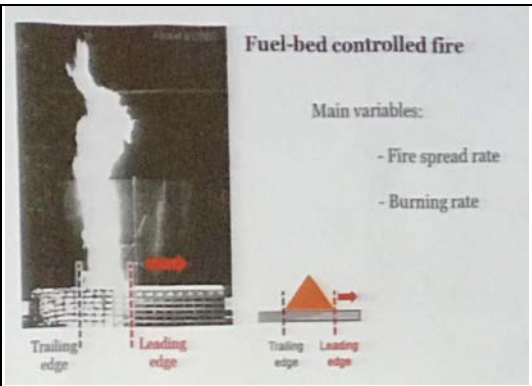
圖 21、 SFPE 主席開場演說

圖 22、 SFPE 夥伴介紹

活動由SFPE主席 John "JC" Harrington開場，依序介紹出席的組織成員、研討會贊助單位及各展出單位，並介紹會務概況，另外也特別說明由美國消防工程師學會台灣分會主辦的第 11 屆亞-澳火災科學與技術研討會(11th Asia-Oceania Symposium on Fire Science and Technology，11th AOSFST)，今年底 10 月 21 至 25 日於台灣台北舉辦，歡迎踴躍參加。另外該會相當重視現代科技的資訊推播，全球相關領域研究者可利用各種網路社群媒體(包括website、blog、facebook、twitter、linkedin、youtube、SFPE event App等)，追蹤討論相關火災科學議題，以即時獲取最新的資訊。

本次研討會文章發表議程如附錄 2 所示，會議資料僅提供各篇文章的摘要，並未提供論文集，且分兩個場地同時進行研討，因此僅能選擇相關議題進入聽講，完整會議各篇文章原文摘要資料彙整於附錄 3，另有 3 篇簡報資料商請簡報者會後提供(列於附錄 4)，茲僅將聽講部分議題摘要彙整如下：

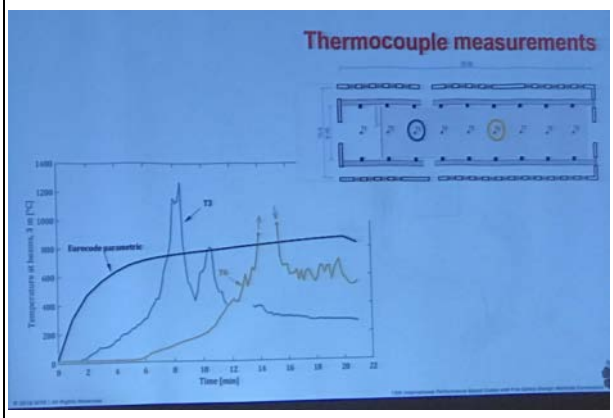
篇名	摘要
x-ONE Fire Experiment in a Very Large and Open-Plan Compartment	波蘭於 2017 年，在大型實際空間內以自然成長火災實驗探討火災蔓延特徵。該試驗在一開放式、高 3.2 m、面積為 380 m^2的舊RC建築中進行。沿空間長向布置連續木框架作為燃料，用熱電偶及紅外線相機測量空間溫度，火從一端點燃並讓其自然成長。由觀察和溫度量測表明火沿著空間長向快速延燒並在點火後 25 分鐘燒到遠端，未觀察到閃火，火勢蔓延的速度並不穩定，但是正在速度逐漸增加。就開放式空間而言，x-ONE是迄今為止進行過最大的火災實驗。 實驗結果，說明傳統規範(標準)，火場溫度假設為均溫，但在大空間，溫度是連續擴散，且包含溫度下降段，火焰延燒應採 Travelling Fires Methodology (TFM)來模擬，並強調需要更進一步的實驗以便更好地理解大空間火力動力學，以更新現代設計。



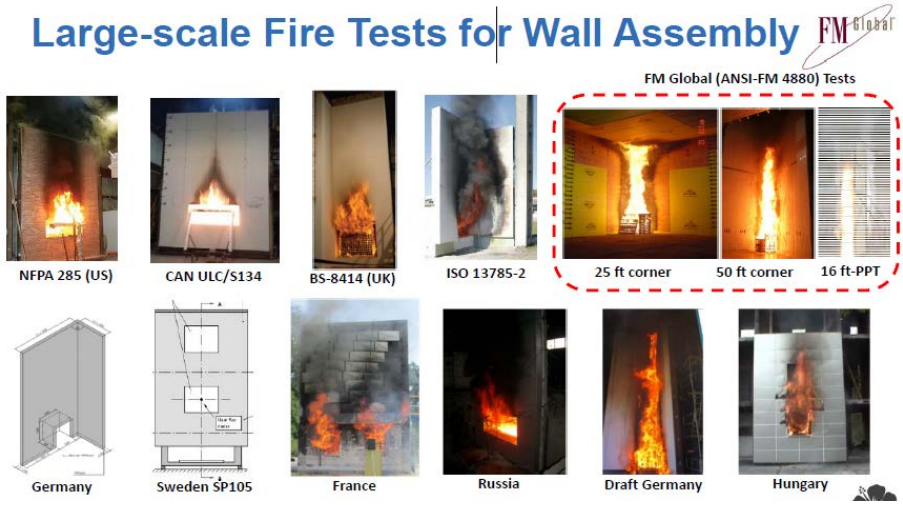
TFM 設計(資料來源:簡報資料)

木框架火源(資料來源:簡報資料)

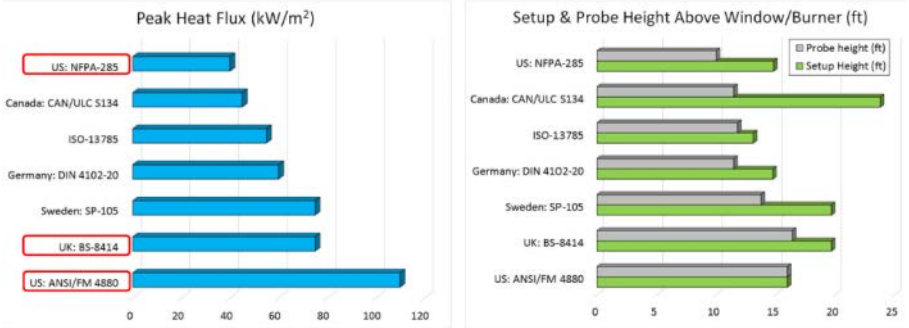
大型實際空間實驗前、後情形(資料來源:簡報資料)



大型實際空間實驗時不同位置溫度曲線(資料來源:簡報資料)

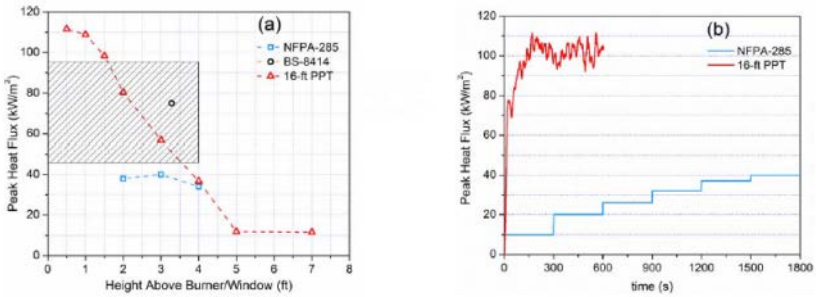
Fire Characteristics in a Tilted Tunnel	為了解傾斜隧道的火災特徵，採用1:40的隧道模型試驗，以丙醇池為火源模擬真正的客車火災。火災特徵包括在不同隧道傾斜角度下的火焰高度、型態、顏色、溫度和蔓延速率。 根據實驗結果發現當傾斜角度改變到一定程度(**4~6˚**)時對火焰蔓延速度有明顯影響；傾斜隧道內的防煙垂壁型式，會影響煙流的擴散；並建議應作熱煙試驗，以更真實的了解煙流行為。
Evaluation of Fire Performance of ACM Wall Assemblies	近期涉及鋁複合材（ACM）牆的高層建築火災已經造成了重大的生命和財產損失。火災事件使國際間努力重新審查建築規範和相應的外牆組件標準防火測試方法。FM Global 在本研究評估 ACM 牆組件的火災危險性，使用 ANSI / FM 4880 的平行板測試（16 英尺 PPT）方法，並比較 NFPA 285（美國）和 BS 8414（英國）的防火測試結果。 測試證明 16 英尺 PPT 可有效評估 ACM 組件火災中的危害。另外結果還顯示，即使通過 NFPA 285，在 16 英呎 PPT 測試中仍可能呈現較高的危害，主要是由於 NFPA 285 測試中採用的熱通量相對低於真實火災情景。  **大型外牆火災試驗類型**(資料來源:簡報資料)

Large-scale Fire Tests - Comparison



大型外牆火災試驗比較 - 試驗最大熱值和組裝/量測高度(資料來源:簡報資料)

Fire Tests Comparison – Heat Flux



NFPA-285 heat flux is lowest

Slow increase of peak heat flux in NFPA-285

大型外牆火災試驗比較 – 試驗熱值和升溫速率(資料來源:簡報資料)

Fire Tests Comparison – Failure Criteria

Test	Peak Heat Flux	Criteria for Fail
16 ft. PPT	~ 100 kW/m²	Peak HRR > 1100 kW
BS-8414	~ 75 kW/m²	Temperature at 16 ft height > 1110 °F
NFPA-285	40 kW/m²	Temperature at 10 ft height > 1000 °F

Approval Installation Height ↓	Test Criteria ↓
Unlimited height	Peak HRR ≤ 830 kW
50 ft	830 kW< Peak HRR ≤ 1100 kW

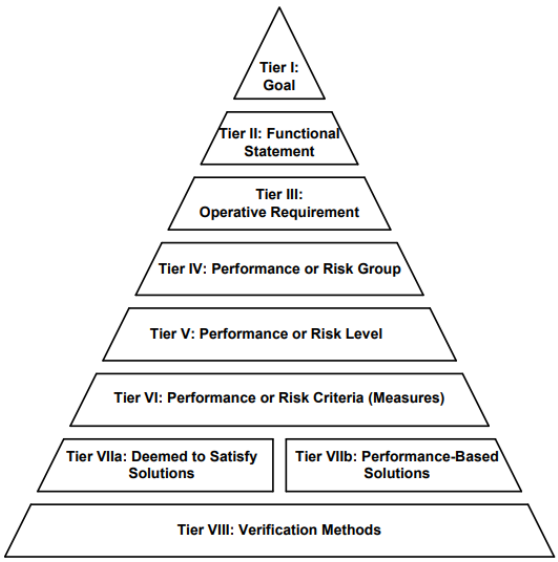
*HRR – Heat Release Rate
Rate of energy release in fires

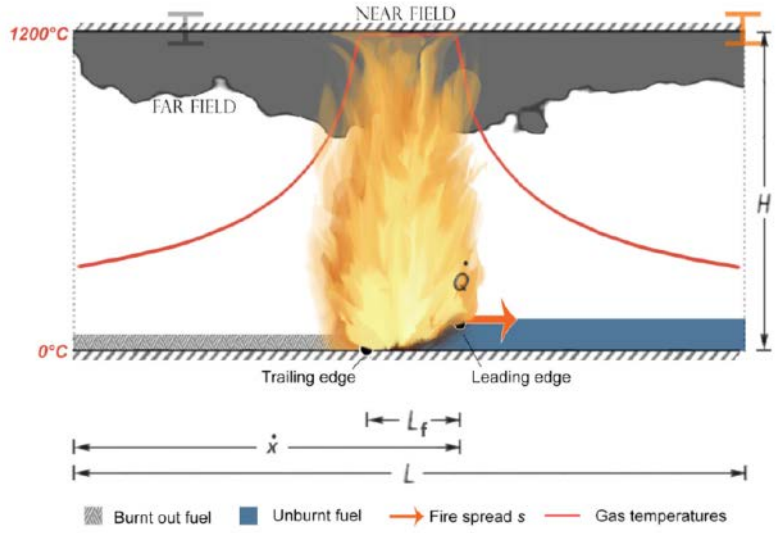
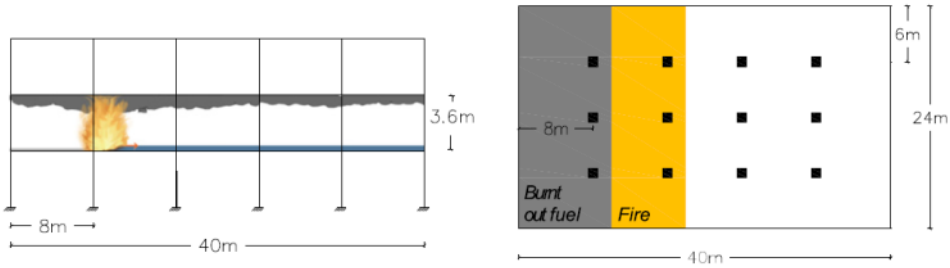
- Global measurement of fire performance.
- Objective and Repeatable.
- Correlated to peak fire propagation height in PPT.

大型外牆火災試驗比較–試驗失敗臨界值(資料來源:簡報資料)

Encounter Media Façade—Performance-Based Fire Hazard Analysis of Exterior Video Cladding Wall	在建築外牆上使用大型LED螢幕進行信息傳遞、廣宣已成為新興趨勢。大尺寸螢幕通常由數百個以聚合材料製成的模塊陣列組成。這種聚合物材料的高可燃性有可能對建築環境造成嚴重的火災危害。雖然製造商聲稱這些螢幕覆層具有UL 94 或等同性的可燃性等級認證，且被視為電子設備。但是，UL 94 的適用範圍清楚地表明它不包括用於建築施工的聚合材料，如牆面和地面覆蓋物等。此外，UL 94 可燃性測試的結果不適用於厚度超過13.0 mm的材料，或表面積超過 1 m^2。 綜整目前對於外牆電視牆所引發的火災和風險的知識，以及相關法規和標準仍然是有限的，未來需加以考量。
Identifying Hazards in Building Facades Containing Combustible Components	因為外牆採用了新型但可能的可燃材料，高層建築外立面的火災可能造成災難性後果，其快速垂直的火焰擴散，會嚴重影響安全疏散和消防滅火。 本篇介紹如何有效利用性能式設計最佳化方法，對此種外立面(資料為超過100個外牆測試的案例)的火災危險，利用AI進行識別和量化，在設計過程中提供給消防工程和建築立面工程參考。 簡報結論指明外牆火災為目前全球性的議題，其設計須與眾多要求平衡，設計的複雜度越高則火災危險性越高，且個別元件性能不等於系統特性，最重要的是目前缺乏此問題的完整研究。
Fire Safety in Tall Buildings – a London Fire Service Perspective	高層建築被認為可以回應很多現代社會的需求問題，這些高層建築每層樓的佈局大體相同，內部同時提供住房和工作空間以及大型開放式娛樂設施等。 高層建築很少完全符合建築和消防規範，消防工程的應用允許專業人員在設計中使用工程技術，提出了合規方法來替代法規規定，並能夠證明這些工程解決方案符合消防安全的基本原則，提供相當於建築規範的功能要求或更高的安全水平。這種方法的主要好處是在空間大

	小，形式，功能和職業方面提供了更大的靈活性。然而，從消防角度來看，這往往會增加挑戰。
Are Verification Methods the Answer to Improved Application of Performance-Based Codes? Be Careful What You Wish For	建築規範應隨時不斷地進行改善審查。建築法規修訂經常是基於維護安全，提高效率和建設的成本效益，並允許使用創新的產品，材料和建築來滿足不斷發展的建築設計景觀。世界各地的大多數規範都是通過這個目標實現的，既可以是規格式的，也可以是性能式的設計方法，也提供不同的級別選項。 澳大利亞已有超過 20 年使用性能式設計的建築規範，可使用性能式設計或符合規格式條款的設計，以滿足性能要求。防火安全工程在這個制度下蓬勃發展，並提高了設計自由度。性能式設計的方法允許火災科學為決策提供信息，並提高設計審核效率。 綜整簡報要點為新材料和創新設計的使用(外覆牆，結構用木構件，模組式營造等)昇高了新的潛在風險並提昇採用驗證方法(Verification Method, VM)對性能式設計的關注。一般 VM 有以下的幫助，基於技術方法建立更多的處理要求、可以驅除不夠專業的消防安全工程師、可以使 AHJ(有管轄權單位)更容易檢視設計結果、可以讓經驗較不足的 AHJ 做出較佳的決定等。 但 VM 仍有可能不會達到符合性能式要求的設計結果，因為它仍然需要依靠從業者的能力做出多種主觀決定. 監管機構必須為所有相關的利益者規定一致的能力，過程和預期文件，並通過持續的教育和執法來改善。
Identifying Implicit Risk in the National Building Code of Canada	本文提出一個架構，以便於識別加拿大國家建築法規（NBCC）性能式規定中可接受的解決方案要求裡隱含的風險，並提供方便 NBCC 從目的式轉向性能式的格式。該架構旨在提供量化手段來彌合現有規格性要求與性能式目標之間的差距。 簡報要點為性能式規定中可接受的解決方案，目前仍存有性能目的未量化，並須確保該解決方案可滿足被替換

	的規定之最低要求。  IRCC Performance-Based Framework (資料來源:簡報資料)
When Can Deemed-to-Satisfy Solutions Make Unsafe Buildings	簡報要點為性能式要求可採性能式解決方案(performance solution)及視為可滿足的解決方案(deemed-to-satisfy solution, DtS)兩種。 許多 DtS 規定，來自對火焰擴散，火災危害和人員反應的知識。但並未考慮到失能者的逃生出口需求，使得失能者在相同建築性能要求下，所獲得的安全等級較低。所以建築規畫者，能否有更多的權利，在 DtS 的規定之外，去要求更多? 更安全的做法。並在當他們發現某些事情是錯誤的時，他們必須採取適當的行動。例如:經測試的構件，在實務上可能只有後面 20 分鐘是處在真實火災狀態，也有可能是後面 10 小時處在真實火災狀態，如果我們採用 60 分鐘做為消防隊的介入時間，則此 DtS 規定可能提供錯誤的訊息。
Connection Behavior in Contemporary Canadian Buildings Subjected to Real Fires	結構性能式防火設計(PBFD)目前在全球有不同的等級被採用。本研究概述一個現代加拿大建築的PBFD案例，該建築係評估了一個範圍內的真實設計火災(包括travelling fire在內)，這是一種嚴重而且可能發生在現代結構的火災類型，但在加拿大很少受到研究關注。本文特別是著眼於整個複合鋼結構建築接頭的行為反應。這些真實情況下的接頭會遇到非常大的軸向性能要求，這在設計時必須考慮，這

	些軸向性能要求的大小和持續時間是不同的，很大程度上係取決於所考慮的火災（standard，parametric和 travelling）類型。無論對建築物的設計方法如何，理解並能夠量化接頭的火災行為情景的範圍，對於確保極端火災事件的彈性結構至關重要。  **Travelling fire和周遭氣體溫度示意圖** (資料來源: Improved Formulation of Travelling Fires and Application to Concrete and Steel Structures，Rackauskaite Egle, Hamel Catherine, Law Angus, Rein Guillermo, 2015)  **試驗時Travelling fire的平面/立面圖** (資料來源: Improved Formulation of Travelling Fires and Application to Concrete and Steel Structures，Rackauskaite Egle, Hamel Catherine, Law Angus, Rein Guillermo, 2015)
Fire Dynamics Simulations for Performance-Based Fire Safety Design of Steel Structures in Large Enclosures	防火規範中的規格式方法是基於防火間隔的概念，不適用於大空間量體。通常採用性能式作為替代的方法，這需要複雜的數值模型來充分模擬結構在設計火災情景下的反應。本文討論應用 FDS 於有大型外殼鋼結構的性能式防火設計。 在中國大陸已有很多性能式的防火設計，但多數僅用簡易火災模型來計算，未考慮結構受熱梯度的影響，在大型挑高建築空間裡，結構受高溫部位有可能僅限於下半部，(局部加熱情形)。在稍早的研究結果知，在標準測試數值模擬，構件呈整體挫曲破壞，在局部火災模擬下，呈局部挫曲破壞。簡報案例研究為北京新建機場，大型挑高桁架鋼結構建築，其構件遭受局部火災之行為分析。

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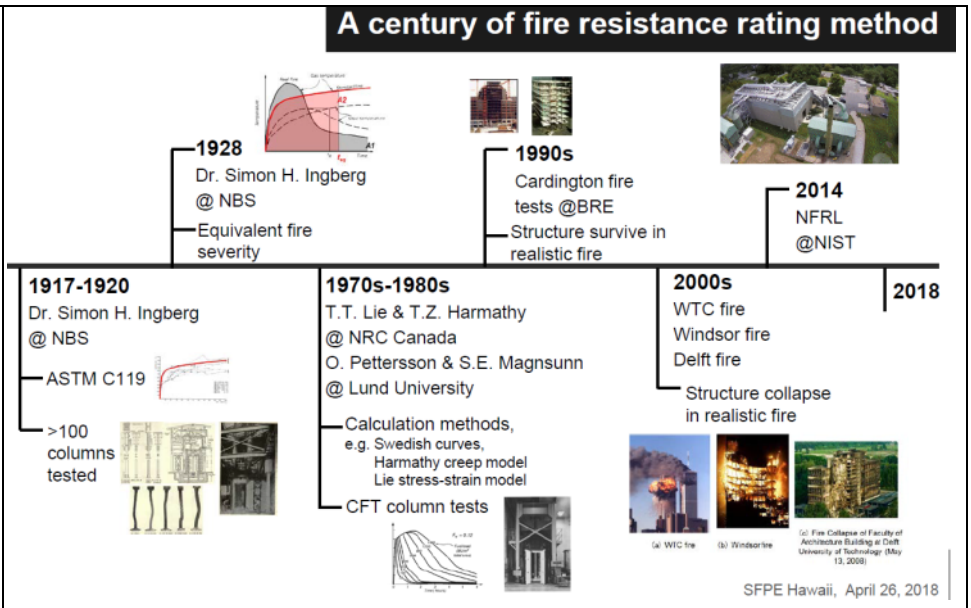
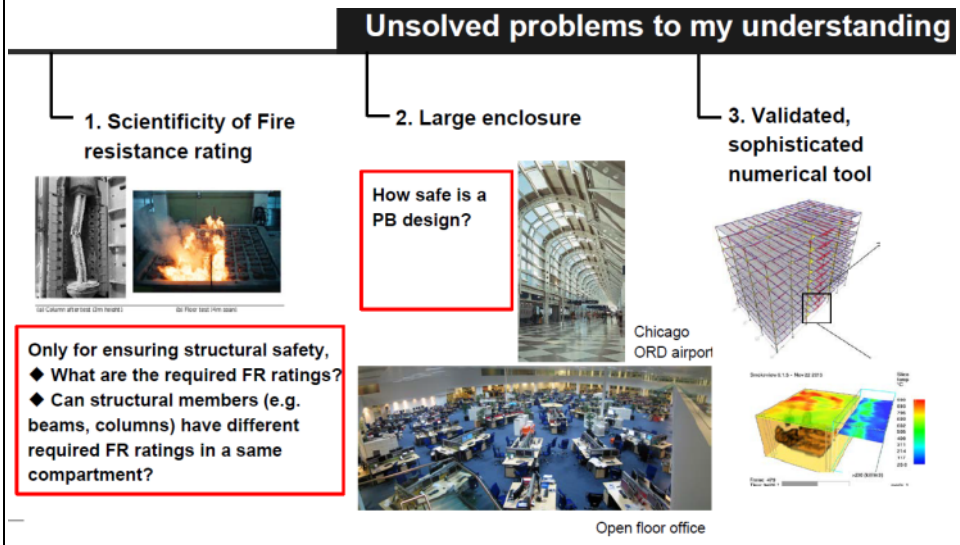


耐火性測試演進(資料來源:簡報資料)


耐火性測試仍需探討的議題(資料來源:簡報資料)
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<td>Performance-Based Fire Resilience Evaluation for a Tall Building Structure</td>
<td>高層建築的興建，隨著過去幾十年多起因火災導致失敗的報告顯示，有必要進行評估規格式設計的有效性。這項研究通過評估高層建築結構的耐火能力數值分析。其目標是分析結構及其法規規定的防火措施在不同的火情中，實際上會如何反應。接下來的目標是確定火災保護是否足夠，或者以性能式設計，看是否可以優化以提高安全性或降低性能方面的成本。這項研究是結合已通過驗證的火災分析工具，包括計算流體動力學的（CFD）和有限元素（FE）。</td>
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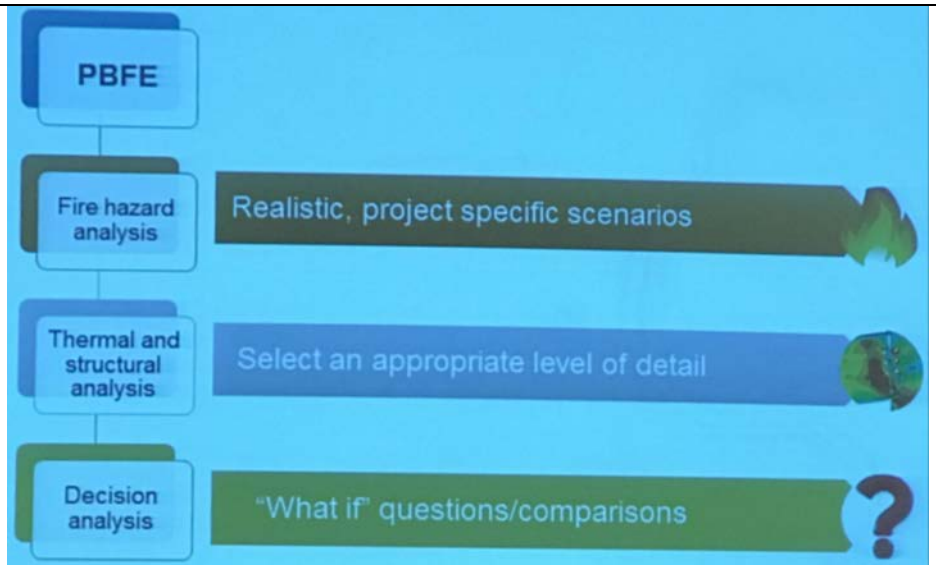
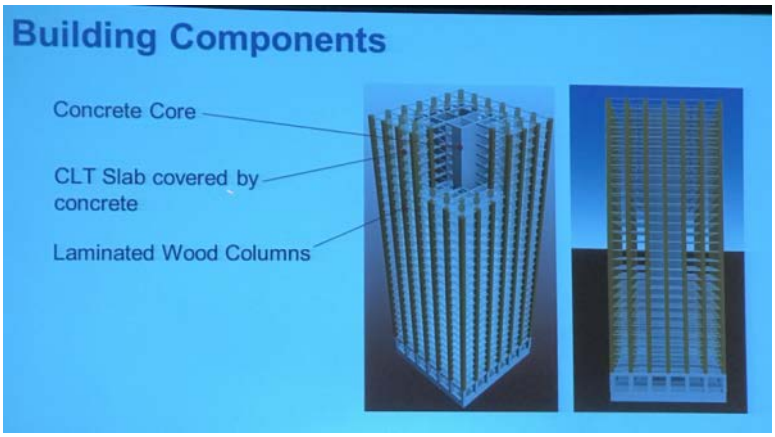
	 **Performance-Based Fire Engineering(PBFE)分析流程** (資料來源:簡報資料)
The Case for Performance-Based Design for Fire Safety	性能式設計帶來新的挑戰，特別是教育，管理和建設批准。雖然規格式法規的方法更容易管理，但本文提出，性能式設計的優點遠大於缺點。通過在許多不同的項目範例中(包括不同建築物的類型和用途)檢驗利用性能式設計對比規格式的法規所取得的利益。簡報所提的案例分析(50 層混合使用鋼構建築)，其結果為對結構整體行為有較定量化的預測，並提供更具彈性和經濟效益的設計。
Performance-Based Fire Safety Design for Dongao Tunnel	臺灣蘇花公路東澳隧道(長 3.38 公里)的性能式消防安全設計，東澳隧道是台灣地區第一個安裝水霧系統和採用點排式排煙控制系統的隧道，因此其整合控制系統非常重要。本研究使用 FDS 模擬火災和煙霧行為並評估設計是否可以通過標準，包括撤離人員、消防員的安全、混凝土和火災蔓延的風險。性能式設計考慮的項目包括斜坡效應、活塞效應、交通堵塞、外部風力效應和相對位置排煙口、水霧區和疏散通道。模擬結果表明，同時使用縱向通風和使用水霧的效果比只使用通風系統的效果更好，同時對人員避難和消防救災有利；另外水霧系統對降低混凝土的溫度，防止混凝土的剝落有很大作用。

Situation with Performance-Based Codes and Fire Safety Design in Seven Countries	簡報要點為以性能為基礎的建築規範（法規）已有越來越多的趨勢，其理由包括可減少監管負擔、降低成本，增加建築材料和設計創新的機會。雖然此法帶來創新，但同一時期，也出現新的監管目標和對建築物的新要求及挑戰。為解決這些問題和挑戰，需對施行性能式設計的當前環境有更好地了解，並識別其建築監管結構的潛在變化以及性能式的分析和設計的實踐。
A Performance-Based Approach for the Design of Engineered Timber in Buildings in the Australian Context	工程木材作為建築材料具有下述優點，永續性、加工和處理效益、美學和結構反應，符合建築環境的趨勢。然而，目前有限的知識和技術，限制了其使用的靈活性和優勢。 澳大利亞通過將視為滿足的解決方案規定（DtS）納入國家建築法規（NCC）來將工程木材用於結構，但限制木材使用於某些建築類別，最大限高 25 米，需設置撒水系統保護，木結構需包覆防火材。 為進一步了解工程木材的防火安全使用，物理測試和實驗提供定量信息支持木結構建築的設計，具有更多的設計靈活性並符合法規的要求。
The Role of Wood Chemistry in Determining the Charring Rates of Timber under Realistic Fire Conditions	CLT 便宜、堅固和永續的特性，有助建造木構造高層建築物，但是它在火災中的行為需更加理解。 對於結構應用，木材炭化率可以用來確定承重能力。依據標準加熱爐和標準加熱曲線測試，炭化率被假定為對所有條件有效的一個定量常數。這個簡化是對工程和性能式設計的嚴重限制。 最近的研究發現標準火災在大型開放空間中並不代表真實的火場情景因此炭化率在真實火災條件下並非為定量，此特性影響木材在真實的火災下的性能式設計。因此評估真正的火災期間的炭化的新工具是需要的。

Performance-Based Design of Fire Safety in High-Rise CLT Buildings	交錯積層材（CLT）帶來了許多新的好處，但防火安全仍然是一個挑戰。本篇著重介紹用 CLT 建造高層建築(十六層以上)引起的消防安全問題。如果木構造暴露於激烈的火災情景，會對承重結構的承載能力產生影響。CLT 建築的另一個挑戰是六層樓以上樓層的結構和被動的防火區畫必須設計成能承受在結構內的移動荷載和風荷載所造成的振動。 雖然 CLT 高層建築的複雜性以及有限的經驗，致使消防安全設計耗時，但是，CLT 建築的施工時間比其他類型的建築結構短。 木材結構，可能會隨著時間的推移而收縮，特別是在第一年的時候，對 CLT 元件的連結處可能會受到影響，需要特別關注。
Case Study – CLT High-Rise	在日本木構造建築對於面積和高度同樣有嚴格限制，面積要小於 3000m^2，高度小於 13m。如超過前述限制，則須具有耐火性能，通常採用不可燃材進行覆蓋。 本案例研究，不採常見的耐火時效(1、2、3 小時)要求，改採 45 分鐘為考量時間，此時間內結構不能倒塌、完成避難逃生及開始滅火行動。  **案例分析的建築形式**(資料來源:簡報資料) 木造高樓建築須考量建築設計(內、外部火災擴散防止)、有效的消防滅火計畫(撒水系統和消防隊)、煙控設

	計和避難逃生規劃。 另外需考量木造高樓倒塌時，會引起城市火災；還有遇到大地震後撒水系統可能故障，無法有效初期滅火，且消防隊可能受地面交通堵塞，無法快速抵達等問題。
Green Roof, A Fire Problem?	綠屋頂覆蓋物的使用，引起了是否不符合瑞典建築規範消防安全的正式要求的研究，目標是要走出目前規定的小尺度測試方法並為性能式設計制定基準。主要結論是，在正常的瑞典氣候條件下，一年中大部分地區的綠屋頂火災蔓延的風險都很低。

參、心得及建議

本次研討會發表討論議題相當廣泛豐富，對於吸取目前世界上相關性能式設計與應用、大空間建築火災行為、建築外牆防火性能與危害分析、CLT 高層木構造防火及綠建築與防火等有很大的收穫。

經過本次參加研討會，有以下的心得與建議，可供後續研究規劃參考：

1. 性能式設計除了傳統上依據其流程架構 – 定義計畫範圍、確立目標、定義目標、發展性能要求、發展火災情境及設計火災、發展試驗設計、評估試驗設計、選擇符合性能要求設計、修改設計或目標及選擇最終設計等步驟進行。在這些步驟中，有些值得進一步的探討，例如發展火災情境及設計火災，有多篇文章提到大空間火災行為與傳統火災假設不同，火場空間可能不會同時劇烈燃燒，需考量 travelling fire 此類火焰連續擴散的影響，還有依據標準構件試驗所獲得的耐火性能，在遭遇局部火災時的性能差異，這些皆須納入性能式設計去考量。
2. 近來對於標準耐火試驗與實際火災差異的檢討也逐漸浮現，目前的標準防火測試，有時又稱纖維素火災，亦即燃燒物主要為纖維素，但現今塑膠、化學及工業等可燃源充斥在各類型的建築內，其所引起的火災成長曲線勢必更嚴重；同時標準防火測試也未考量降溫段對構件或結構的影響；另外火災的嚴重程度也與火場通風有關，這些差異在性能式設計時均應依據各案加以探討，以獲得最佳且安全的防火設計。
3. 受到 2017 年英國 Grenfell tower 大火影響，多篇文章探討外牆防火，此主題與其他篇文章如大型戶外電視牆、綠屋頂或綠色植生牆等所引起的火災危害亦為相關，而國內近來因應氣候變遷，部分建築外牆增設具有隔熱效果的外覆牆，其所引起的相關防火性能值得加以探討，包括其安裝的法令規定、設置的防火性能標準、對應的標準試驗以及後續使用維護注意事項等。

4. 工程木材(如 CLT)作為建築材料具有下述優點，永續性、加工和處理效益、美學和結構反應，符合建築環境的趨勢。然而，目前有限的知識技術和相關法令，限制了其使用的靈活性和優勢，例如在面積和使用高度上受限，另外木構造高層建築須考量建築設計(內、外部火災擴散防止)、有效的消防滅火計畫(撒水系統和消防隊)、煙控設計和避難逃生規劃，以降低火災的危險度。

附錄

相關資料

附錄 1　Poster Session

Roadmap for Incorporation of Risk Criteria and Analysis in Building Regulatory Decisions

Brian Meacham, Meacham Associates, USA, and IJsbrand van Straalen, TNO, the Netherlands

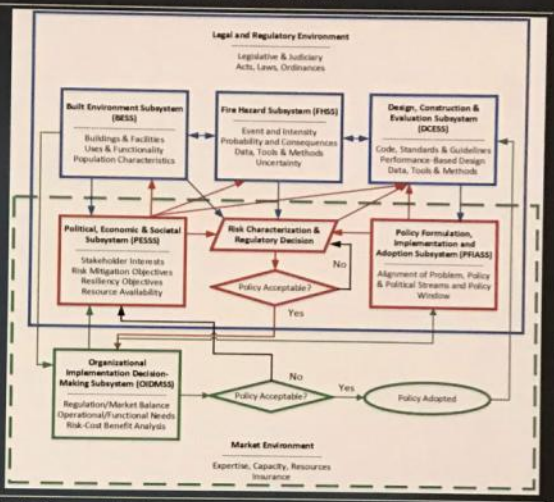
It has been suggested that future generations of building regulations can become more risk-informed and performance based, and that development of the regulations and the risk bases that underpin them should occur within a socio-technical systems framework.

To facilitate this, it is important for regulators and the market to understand and agree the risk measure(s) that will be used to define the risks, the specific risk criteria that will be used in the evaluation of the risks, and the analysis and design approaches that will be used to demonstrate that building design solutions can be verified as meeting the risk criteria and measures. As one might expect, there are a number of complicated factors that materially affect the identification, implementation and certainty of quantified risk criteria for use in regulation and the application of risk-informed and risk-based design, respectively.

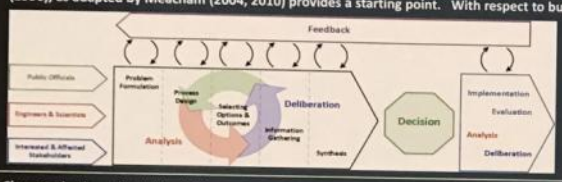
Meacham and van Straalen (2017) present a set of eight steps that can facilitate incorporation and acceptance of risk criteria and methods in a broadly universal manner within the context of the STBRS framework:

- Step 1. Understand the Legal Culture (Civil/Common Law, Regulatory Approach)
- Step 2. Understand the State of Knowledge (BESS, FHSS, DCESS)
- Step 3. Understand the Market (OIDMSS)
- Step 4. Identify Appropriate Risk Characterization Method (PFIASS, PESSS, Risk Characterization)
- Step 5. Select Criteria and Methodology Pairing(s) (FHSS, BESS, PESSS, Risk Characterization)
- Step 6. Undertake Risk Characterization / Quantification (Risk Characterization)
- Step 7. Identify or Develop Risk-Informed Design Methods (FHSS, Risk Characterization, DCESS)
- Step 8. Evaluation and Implementation

However, additional guidance on risk characterization can be helpful in the process.



Characterizing risk requires value judgments. Ultimately, risk decisions are significantly policy decisions – whether in government or private-sector entity – that are informed by analytical data and stakeholder deliberation regarding the hazards of concern and the values of the society or entity. The risk characterization framework of Stern and Fineberg (1996), as adapted by Meacham (2004, 2010) provides a starting point. With respect to building regulations, a primary concern is risk to life (or, providing safety to life), as related to various health and safety hazards and hazard events. In some cases, property protection is a concern as well. In this work the focus is on risk to life. When dealing with safety to people, risk of injury or death are common risk measures.



To gain acceptance on risk to life measures, it will be necessary to have an interplay between experts and the public to gain agreement on who is at risk, from what, how to quantify, what data are acceptable, what methods of assessment or estimation are acceptable, and how the resulting risk estimates are to be used. Historical data, perceptions of risk, social equity, vulnerable populations and reliability of technology are likely to play a role in the process.

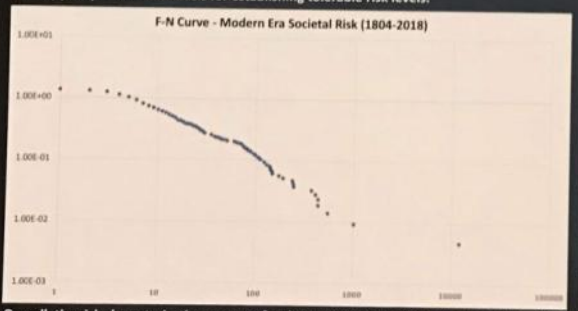
Characterization of individual risk can be accomplished in several ways. The approach will depend on the way in which the risk information will be presented. For example, it can be characterized as 'annual risk of death' by using a country's annual mortality and population data (number of deaths by source across the population divided by the total population).

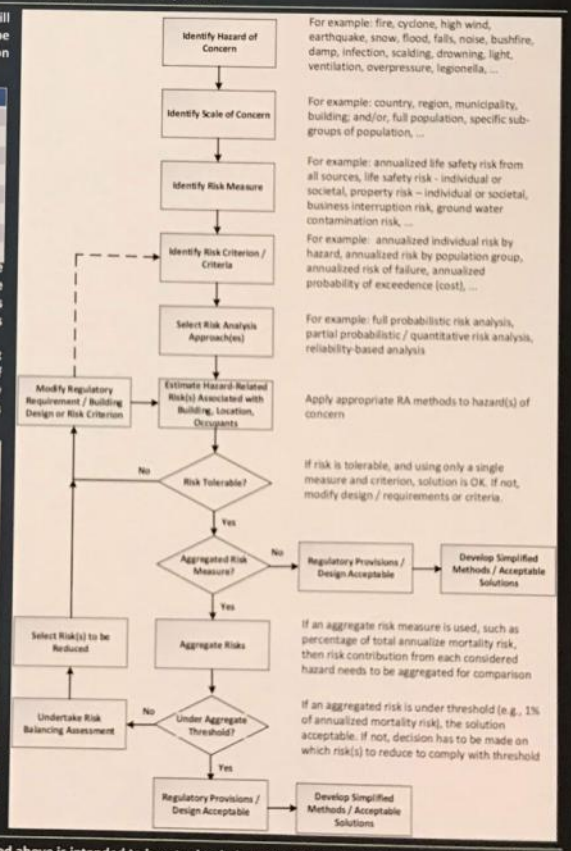
Alternatively, a time basis average can be used (e.g., risk over a 10-year period), or risk can be considered for different groups (i.e., by age or gender), or it might be considered only for a single event type (e.g., fire) or across a wide range of events or sources (e.g., building hazard, natural hazard, health).

Hazards in Buildings Leading to Death	2015
Falls	2.27E-05
Mechanical Forces (e.g. failures)	3.17E-06
Drowning	3.17E-06
Fire	2.38E-06
Forces of Nature (e.g., hazard from wind)	1.38E-06
Electricity and Temperature	4.59E-07
Hot Surfaces	2.51E-07
Total	3.32E-05

A limit-state approach can also be used, wherein the risk is assessed in terms of the relationship between the probable exposure (load) and the resistance to that exposure (e.g., probability of a fire resulting in structural failure leading to loss of life). Various disciplines have established criteria based on individual risk, including chemical process safety, environmental health hazards, occupational hazards, and structural safety.

In much of the literature, characterization of societal risk is largely based on the concept of an F-N curve, where generally F is the frequency of a particular hazard, event or type of event, and N is the number of fatalities, given that hazard, event or type of event. Generally speaking, the F-N curve does not establish the risk criterion itself; rather, the F-N curve is used by policy-makers as a basis for establishing tolerable risk levels.





Overall, the risk characterization process, for the purpose of establishing risk metrics within building regulation, follows the map as illustrated in the flowchart to the right. Hazards of concern are identified, risk measures selected, risk analysis undertaken, and deliberation and decision on tolerability of risk is undertaken. If tolerable, the measures can be incorporated into regulation, or otherwise cited within the building regulatory system.

There is growing interest in using risk as a basis of building regulation. The roadmap presented above is intended to be a tool to help guide building regulators, as well as practitioners, in using risk as the basis of performance objectives in building regulation, and in undertaking and verifying designs for compliance with risk criteria. Aspects of the roadmap are being tested, and a more complete discussion, with examples, will be published in the near future. Please refer to the extended abstract in the SFPE proceedings for references cited above. Meacham and van Straalen, "Roadmap for Incorporation of Risk Criteria and Analysis in Building Regulatory Decisions," *12th International Conference on PB Codes and FS Design, SFPE*.

A COST BENEFIT TOOL TO ANALYSE SPRINKLERS AS AN OPTION IN THE DESIGN OF BUILDINGS

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BRANDKONSULTEN

Brandkonsulten AB has developed a model aimed to investigate whether it is economically beneficial to provide a building with an automatic fire sprinkler system at an early stage of a construction project, even if it is not a requirement in the local building code.

The model analyses the cost savings that can be made with an automatic fire sprinkler installation based on reducing other requirements in fire protection for the building based on either analytical design or code-allowed easements.

The model is primary a tool for property owners and general contractors and includes cost for installation, operation and maintenance, building costs and impact on leasable area over a selected period of time. The time period is chosen based on the time frame of the investment in the property.

The model shows that there can be major financial benefits in installing an automatic fire sprinkler system in a building.
In geographic areas where prices for leasable floor units are higher per square meter, it is more beneficial to install an automatic fire sprinkler system if it can create more leasable area, for example by removing a stairwell. On the other hand, in areas where the price for leasable floor is lower, it can be of interest to reduce the construction costs, for example by reducing the fire rating of glass, increasing fire compartments (i.e. fewer fire compartment walls, fewer doors with fire rating classification and fewer smoke dampers).

EXAMPLE BUILDING

FLOW CHART OF THE DIFFERENT STEP OF THE MODUL

Analysis of fire protection requirements without sprinkler

▼

Analysis of fire technology simplifications that can be carried out with sprinkler

▼

Retrieving information about costs for the simplifications that can be carried out with sprinkler installation

▼

Summary of costs with or without sprinkler installation

WHICH PARAMETERS THAT ARE AFFECTED BY AN AUTOMATIC FIRE SPRINKLER INSTALLATION

	Without sprinkler installation		With sprinkler installation	
Additional costs for construction and installations				
Stairwell (quantity)	1	400 000 sek	0	0
Fire compartement walls, excluding glass partitions (m2)	220	45 000 sek	0	0
EI 60 glass/window (m2)	340	1 700 000 sek	0	0
Sprinkler installation (m2)	0	0	6100	2 200 000 sek
Fire rated door (quantity)	11	70 000 sek	0	0
Total cost		**2 210 000 sek ~ $ 276 000**		**2 170 000 sek ~ $ 271 000**
Lost revenue for leaseable area				
Stairwell (m2)	52	3 600 000 sek	0	0
Sprinkler control room, basement (m2)	0	0	20	700 000 sek
Lost revenue		**3 600 000 sek ~ $ 450 000**		**700 000 sek ~ $ 87 500**
Impact on operation and maintenance				
Sprinkler system	0	0 sek	1	120 000 sek
Total cost		**0 sek ~ $ 0**		**120 000 sek ~ $ 15 000**
Total additional cost		**6 000 000 sek ~ $ 750 000**		**3 000 000 sek ~ $ 375 000**

Brandkonsulten is one of the leading consultants in fire safety and risk management in Sweden

Evaluation of the Fire Resistance for Simple Beams built with TMC Fire Resistant Steels using Fire Engineering Techniques

INKYU KWON

Professor, Dept. of Fire Protection Engineering, Kangwon National University, KOREA

ABSTRACT

It is well known that a structural steel has high strength as well as good construction efficiency. However, when it or a steel framed building exposes to a fire situation, the merit of strength will disappear and disasters such as life losses and property damages may occur. Therefore, the fire resistance of the structural steels or steel frames should be satisfied with building regulations or building codes. In this paper, to evaluate the fire resistance of structural beams built with new developed structural steels such as a TMC FR490 steels, FR490 steels having a better fire resistance performance than that of conventional one, a fire engineering technique was applied. The results were shown that FR 490 steels revealed superior to that of TMC FR490, SM490, and SS400.

INTRODUCTION

In this study to quantify the structural fire behaviors at high temperatures according to sorts of structural steels, boundary conditions, lengths, a fire engineering method was used. This method is well known as a rational and advanced tool to evaluate the structural fire performance using not only a mechanical and a thermal property at high temperature but a heat and thermal stress analysis. A research project has started to make a guideline of a structural fire engineering design in Korea since 2015 and it is expected that the guideline will be done within few years later.

METHODS

Figure 1. Test device for mechanical properties

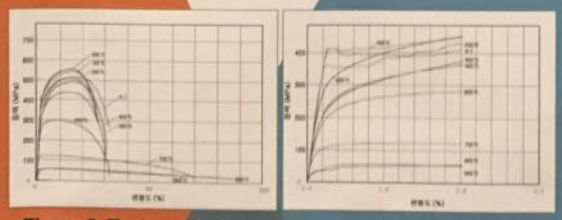


Figure 2. Test results for stress versus strain at various temperatures

Table 1. Models for mechanical/specific heat properties

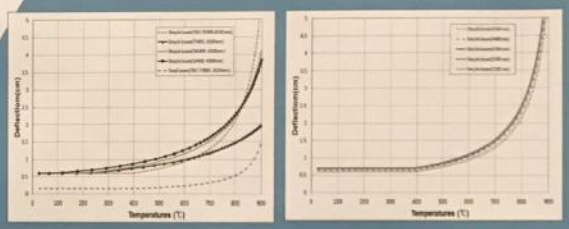
Properties	Temperature	Regression equation
Yield strength	T≤300℃	Cold value (330 MPa)
	300℃<T	-0.41T + 437.46
Elastic modulus	T≤400℃	Cold value (210GPa)
	400℃<T	-0.37T + 360.75

Temperature (℃)	Regression equation (E-03/℃)	Remarks
T ≤600	0.0006T + 0.4	R^2=0.94
600 < T ≤700	0.006T - 2.86	R^2=1
700 < T ≤800	-0.003T + 3.33	R^2=1
800 < T	-0.002T + 2.37	R^2=1

ANALYSIS

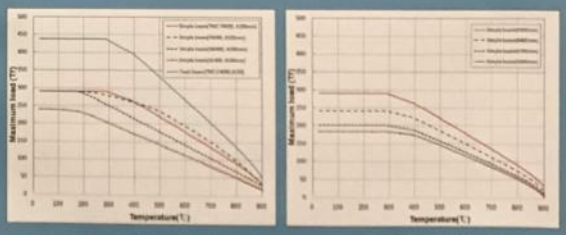
Table 2. Calculation process of deflections and maximum loads according to temperature differences

RESULTS



(a) Various types **(b) TMC FR 490**

Figure 3. Deflections versus surface temperatures



(a) Various types **(b) TMC FR 490**

Figure 4. Maximum loads versus surface temperatures

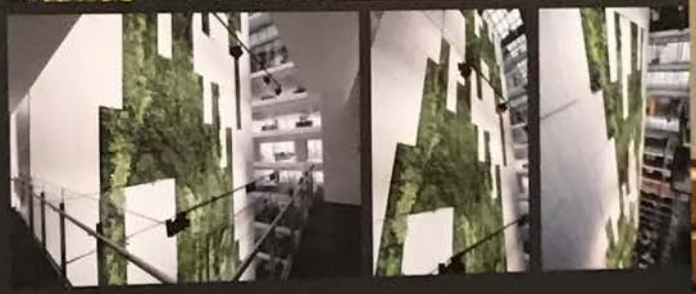
CONCLUSIONS

1. A beam built with a TMC FR490 showed a better performance in the range of up to 650°C than other structural steels but in the subsequent range, the deflection was increased rapidly. As the lengths of the TMC FR490 were going to longer, the deflections were increased too. But the differences were not great enough.

2. A beam built with a TMC FR490 revealed a better performance by 400°C but in the subsequent temperature range the maximum load carrying capacity was going down and a little lower than that of FR490. The length of beam was longer, the maximum capacity was down rapidly and it was clear that fire resistant performance getting from a standard fire test specimen cannot ensure the same fire resistant from other size beams. Therefore, a real size fire test or an analytical engineering method should be recommended.

Irrigation systems for life safety?

Design + Approval of 60m Green Wall in an Internal Office Atrium



What is a Green Wall + Why

- Vertical structure of live plants and greenery
- Integrates nature into the urban built environment
- Improves indoor air quality
- Passively assists cooling systems
- Boosts noise absorption, reducing reverb, and improving office quality
- Increases quality of building, occupant well being, and productivity

Is it a fire life safety risk?

- Essentially an internal, combustible, polyurethane foam façade without any protective rendering
- Major fire spread risk - spans a 16 storey space
- Occupant life safety risk as the majority of floors are open to the atrium

Our final fire safety design

- Additional sprinkler protection throughout wall – vertical side walls facing the panels – however it's not a tested use
- 100m³/s of smoke exhaust
- Point type and beam smoke detectors
- Redundant irrigation system, with 24/7 monitoring and support, and integration to the fire control panel. Irrigation system failure results in building evacuation after a time delay
- Reduced ignition sources, no lighting in wall, and vertical exclusion zone at low level where the wall is readily accessible
- Requirement for quarterly inspections by a registered Fire Safety Engineer
- Significant additional fuel load: 1kg of foam panel approximately equals 1 kg of petrol in fuel load energy density

Analysis + Approvals

- High risk design, initially delayed and then rejected by the fire brigade and raised to the Buildings Appeals Board (BAB), initially rejected with written comments
- Quantitative risk analysis – showed very low probabilities, but full quantification of individual valve failure rates was problematic
- FDS modelling – difficult to predict fire spread rate or peak heat release rate, significant conservatisms utilized
- Held an in-person tribunal with the BAB leading to an open discussion of concerns, main issue was future reliability
- Undertook a qualitative reliability study, and redesigned the irrigation system to achieve reliability to a similar standard as a fire life safety system. Resulted in final design (below)

Our Green Wall

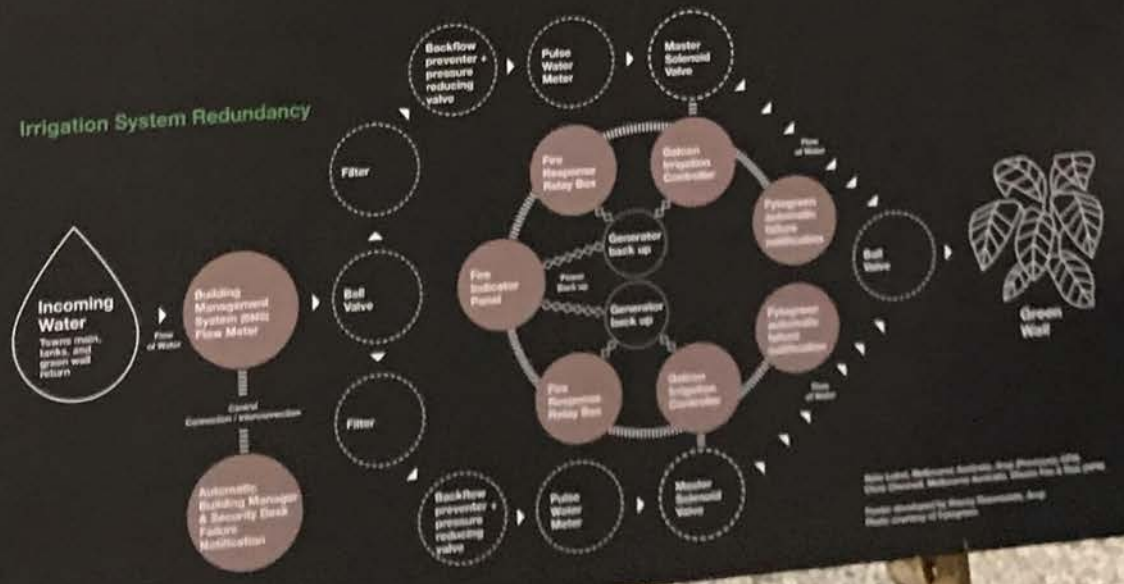
When wet, panels hold in approximately **30% water** by volume

~60m tall internal atrium mostly open to floor plates

Over **450m²** containing over **13,500** plants

Felt wrapped **polyurethane** foam panels (substrate)

Irrigation System Redundancy



附錄 2 研討會文章發表議程

Day 1 - Wednesday, April 25		
0715-0755	Breakfast in Exhibit Area (Tapa 1)	
General Session - Tapa 2		
0800-0805	**Welcome and Introductions** – Nicole Boston	
0805-0820	**Welcome Remarks and Conference Kick-Off** - JC Harrington, Sam Dannaway, Peter Johnson, and Brian Meacham	
0820-0855	**Marco Polo High Rise Fire, Prevention, Preparedness, and Response** - Manuel Neves	
0900-1000	**Track A in Tapa 2 - New Research** Moderator: Peter Senez	**Track B in Tapa 3 - Performance-Based Design Applications** Moderator: Paul Hart
0900-0925	**x-ONE Fire Experiment in a Very Large and Open-Plan Compartment** - Egle Rackauskaite & Nieves Fernandez Anez	**Performance Based Design in Support of an Alternative Method for Laundry Chute Ventilation** – Steven Whitman & Scott Knight
0925-0950	**Fire Characteristics in a Tilted Tunnel** – WK Chow	**Fire Engineering Challenges during Redevelopment of Existing Shopping Centers** – Alexander Alexandrovski
0950-1000	**Q&A Discussion**	**Q&A Discussion**
1000-1030	Morning Coffee Break in Exhibit Area	
1030-1230	**Track A in Tapa 2 – Building Facades –** Moderator: Sam Dannaway	**Track B in Tapa 3 – Probabilistic Methods –** Moderator: Jonathan Barnett
1030-1055	**Evaluation of Fire Performance of ACM Wall Assemblies** – Yi Wang & Richard Davis	**A Quantified Risk-Based Framework for Life Safety** – Ijsbrand Van Straalen & Brian Meacham
1055-1120	**Encounter Media Façade: Performance-Based Fire Hazard Analysis of Exterior Video Cladding Wall –** Frank Wang	**A Holistic Approach to Fire Risk Assessment: How to Combine Bow-Ties of Standard Fire Scenarios to Develop a Creative Yet Robust, Barrier Based, Fire Safety Strategy –** Luca Fiorentini
1120-1145	**Identifying Hazards in Building Facades Containing Combustible Components** – Matthew Bonner	**Risk-Informed Airport Fire Engineering Solutions of Operational Continuity –** David Charters & Alan Sheach
1145-1210	**A Performance-Based Approach to Fire and Life Safety for the New International Terminal at Calgary International Airport**– Peter Senez	**New Anglo-Polish Methodology for Fire Risk Index Evaluation for Fire Strategies** – Dorota Brzezinska & Paul Bryant
1210-1230	**Q&A Discussion**	**Q&A Discussion**
1230-1330	**Networking Lunch in Exhibit Area** **Sponsored by** JENSEN HUGHES Advancing the Science of Safety	

General Session – Tapa 2	
1330-1415	**A Tribute to Margaret Law –** Jose Torero
1415-1455	**Case Study: Hospital Fire Protection** – Moderator: Ijsbrand Van Straalen • Case Study – Finland
1455-1525	Afternoon Break in Exhibit Area
General Session – Tapa 2	
1525-1605	**(Cont'd) Case Study: Hospital Fire Protection** – Moderator: Ijsbrand Van Straalen • Case Study – Italy
1605-1700	**Case Study Panel Discussion – Hospital Fire Protection**
1700	Day 1 Wrap Up - TBD
1700-1830	Networking Reception in Exhibit Area

Day 2 – Thursday, April 26		
0715-0755	Breakfast in Exhibit Area	
General Session in Tapa 2		
0800-0810	**Welcome and SFPE Foundation** - Peter Johnson, Brian Meacham, & Peter Senez	
0810-0845	**Fire Safety in Tall Buildings—a Fire Service Perspective** - Kevin Hughes	
	Track A in Tapa 2 - Working within Building Regulations Moderator: Ijsbrand Van Straalen	**Track B in Tapa 3 - Fire Protection Systems** Moderator: Jose Torero
0850-0915	**Are Verification Methods the Answer to Improved Application of Performance-Based Codes? Be Careful What You Wish For** - Peter Johnson & Nate Lobel	**Performance-Based Design: Testing of CPVC Sprinkler Piping for Concealed Spaces in a High Rise Historical Building** - John Crompton
0915-0940	**Identifying Implicit Risk in the National Building Code of Canada -** Keith Calder	**Using BIG Data for Automatic Fire Alarm System Response Strategies** - Böðvar Tómasson, Sveinn Björnsson, & Björn Karlsson
0940-1005	**When Can Deemed-to-Satisfy Solutions Make Unsafe Buildings -** Jonathan Barnett	**Smoke Management in Detention Facilities -** Steven Dannaway
1005-1020	**Q&A Discussion**	**Q&A Discussion**
1020-1050	Morning Coffee Break in Exhibit Area	
	Track A in Tapa 2 - Structures and Fire Protection Moderator: Joseph Vaughn	**Track B in Tapa 3 - Human Behavior** Moderator: Samuel Dannaway
1050-1115	**Connection Behavior in Contemporary Canadian Buildings Subjected to Real Fires** - John Gales	**Walking Speed in Smoke: Representation in Life Safety Verifications** - Karl Fridolf
1115-1140	**Fire Dynamics Simulations for Performance-Based Fire Safety Design of Steel Structures in Large Enclosures** - Chao Zhang, Hong-Xia You, & Lisa Choe	**Beyond ASET vs RSET: Performance-Based Fire and Crowd-Flow Safety Design of Large Scale Stadiums** - Yoshikazu Minegishi
1140-1205	**Performance-Based Fire Resilience Evaluation for a Tall Building Structure** - Jenny Sideri	**Practicalities and Limitation of Coupling FDS with Evacuation Software** - Daniel Blixt & Daniel Rådemar
1205-1220	**Q&A Discussion**	**Q&A Discussion**
1220-1320	Networking Lunch in Exhibit Area	
General Session in Tapa 2		
1320-1405	**Evolution of the Building Code: From First Principles Design to Verification Methods** - Christine Duncan	
	Track A in Tapa 2 - Implementing Performance-Based Design Moderator: David Charters	**Track B in Tapa 3- CFD Modeling** Moderator: Paul Hart
1405-1430	**The Case for Performance-Based Design for Fire Safety** - Marianne Foley	**Accounting for Uncertainty in Computational Fluid Dynamics Modelling of Fully-Developed Compartment Fires** - Vinny Gupta
1430-1455	**Performance-Based Fire Safety Design for Dongao Tunnel** - Wei-Ting Chung & Kuang-Chung Tsai	**A CFD Study to Identify Methods to Increase Maximum Velocity of Make-up Air for Atrium Smoke Control** - Christine Pongratz
1455-1520	**Taking a Performance-Based Approach to the Protection of a Membrane Roof Aircraft Hanger--A Case Study** - Craig Vesely	**Fire Safety Upgrades of Underground Railway Systems** - Felix Gamon
1520-1535	**Q&A Discussion**	**Q&A Discussion**
1535-1605	Afternoon Break in Exhibit Area	
General Session in Tapa 2		
1605-1725 1605-1645 1645-1725	**Case Study: Cross-Laminated Timber (CLT) High-Rise** - Moderator: Chris Jelenewicz • Case Study – Japan • Case Study – New Zealand	
1725-1730	Day 2 Wrap Up - TBD	
1800-2000	Hawaiian Dinner on the Great Lawn	

Day 3 – Friday, April 27		
0715-0755	Breakfast in Expo Area	
General Session - Tapa 2		
0800-0840	**Fire Safety Standards – The Need for Global Consistency -** Gary Strong	
0840-1000 0840-0920 0920-1000	**Case Study: Cross-Laminated Timber (CLT) High-Rise -** Moderator: Chris Jelenewicz • Case Study – USA at UNC Charlotte • Case Study – Hong Kong	
1000-1030	Morning Coffee Break in Exhibit Area	
General Session - Tapa 2		
1030-1130	**Case Study Panel Discussion – CLT High-Rise Fire Protection** - Moderator: Chris Jelenewicz	
	Track A in Tapa 2 - Engineered Wood Moderator: Kiyoshi Fukui	**Track B in Tapa 3- Software Tools** Moderator:
1135-1200	**A Performance-Based Approach for the Design of Engineered Timber in Buildings in the Australian Context** - Mario Lara Ledermann & Nathan White	**Fire Safety Engineering and Building Information Modelling--Now and in the Future** - Andrej Cebela & Judith Schulz
1200-1225	**The Role of Wood Chemistry in Determining the Charring Rates of Timber under Realistic Fire Conditions** - Franz Richter	**Smart Building Systems, Real-Time Data Collection and the Use of a Hierarchical Temporal Memory Continuous Learning Algorithm for Fire State Determination** – John Crompton
1225-1235	**Q&A Discussion**	**Q&A Discussion**
1235-1330	Networking Lunch in Exhibit Area	
	Track A in Tapa 2 - Engineered Wood / Green Roofs Moderator: Kiyoshi Fukui	**Track B in Tapa 3 - Facing Fire Protection Challenges** Moderator: Armelle Muller
1330-1355	**Performance-Based Design of Fire Safety in High-Rise CLT Buildings** - Robert Jönsson & Carl Pettersson	**Evaluation of the Fire Resistance for Simple Beams Built with TMC Fire Resistant Steels Using Fire Engineering Techniques** - In-Kyu Kwon
1355-1420	**Finite Element Modelling of Post-Tensioned Timber Beams Under Fire Conditions** - John Gales & Hailey Quiquero	**Space Familiarity and Exit Familiarity for Emergency Egress -** Haejun Park
1420-1445	**Green Roof, A Fire Problem?** - Jennie Forslund & Daniel Hakansson	**The Birmingham Gateway Project- Managing Construction Fire Safety within Highly Complex and Densely Occupied Infrastructure Projects** - Reece Walker
1445-1500	**Q&A Discussion**	**Q&A Discussion**
General Session - Tapa 2		
1500-1540	**Situation with Performance-Based Codes and Fire Safety Design in Seven Countries** - Brian Meacham	
1540-1600	**Conference Wrap Up** - Peter Johnson & Brian Meacham	

附錄 3 研討會文章摘要

x-ONE Fire Experiment in a Very Large and Open-Plan Compartment

Egle Rackauskaite, MEng, PhD, Research Associate, Imperial College London

In September 2017, a large scale fire experiment x-ONE was conducted in Poland to capture experimentally a natural fire inside a large real compartment and study its fire spread characteristics. The experiment was conducted in an old concrete farm building with an open floor area of 380 m² and a height of 3.2 m. Continuous wood crib arrangement along the length of the compartment was used as the fuel load. The fire compartment was instrumented with thermocouples and visual and infrared cameras to measure the thermal exposure in the compartment. The fire was ignited at one end of the compartment and allowed to develop naturally. Visual observations and thermocouple measurements indicate that the fire travelled fast along the length of the compartment and burned out at the far end 25 min after the ignition. Flashover was not observed. The spread rate of the fire was not constant but was gradually increasing. x-ONE is the largest fire experiment in terms of open-plan compartment floor area carried out to date. It highlights the need for further experiments in large compartments in order to gain a better understanding of fire dynamics, which could be incorporated in the design of modern structures.

Fire Characteristics in a Tilted Tunnel

W.K. Chow, Research Centre for Fire Engineering, The Hong Kong Polytechnic University

To understand the fire characteristics in a tilted tunnel, a 1:40 scale model of a tunnel was used in the experiment to simulate a real passenger car fire by using a propanol pool as the fire source. The fire characteristics including flame height, flame pattern, flame colour, temperature and flame spread rate within a tilted tunnel of different inclination angles were studied. In the experimental study, wood crib being a passenger car adjacent to the fire source was used to study the effect of fire with variation of the tilted tunnel angle. Based on the experimental result, the fire characteristics were evaluated. It was found that there was an apparent effect on the flame spread rate when the inclination angle was changed to a certain degree. Other characteristics, such as the temperature change, flame height, flame pattern and flame colour were also discussed in this paper.

Evaluation of Fire Performance of ACM Wall Assemblies

Yi Wang, PhD, Research Group Manager, Fire Hazards and Protection, FM Global & Richard Davis, PE, FSFPE, MASCE, Senior Engineering Technical Specialist, FM Global

Recent catastrophic high-rise building fires involving Aluminum Composite Material (ACM) wall assemblies, have caused significant life and property losses. The fire incidents warrant an international effort to reinvestigate and scrutinize building codes and the corresponding standard fire testing methods for external wall assemblies. This research evaluates the fire hazards of ACM wall assemblies using the 4.9 m (16 ft) high parallel panel test (16-ft PPT) method of ANSI/FM 4880 [1], and compares the results with NFPA-285 [2] (US) and BS-8414 [3] (UK) fire tests. Seven ACM assemblies, with a combination of three types of ACM panels, two continuous insulations, and a water/weather resistant barrier are evaluated. The tests demonstrate the effectiveness of the 16-ft PPT in evaluating the fire hazard of ACM assemblies, clearly differentiating the fire-resistant systems from hazardous assemblies. The results also show that some assemblies that have passed NFPA-285 perform inadequately in the 16-ft PPT primarily due to the relatively low heat flux exposure in NFPA-285 test as compared to realistic fire scenarios.

Encounter Media Façade—Performance-Based Fire Hazard Analysis of Exterior Video Cladding Wall

Xiaolei Chen, PhD, Assistant Professor, California State University & Frank Wang, PE, Senior Fire Protection Engineer, JENSEN HUGHES

Using large LED video screen on the exterior wall of building for information delivering, advertising and story-telling has become an emerging trend in the façade design of contemporary buildings. The first video cladding wall, a 10-story LED video screen, was installed on the NASDAQ Marketsite building in Times Square in 1999. With the rapid development of LED technology, large video cladding has been adopted worldwide. Media facade is becoming a new fantasy in urban landscape.

Large-screen video screen typically consists of hundreds and thousands of pixel modules/arrays that are made of polymeric materials. The high combustibility of polymeric materials in such systems may pose severe fire hazards to the built environment, bringing in significant life safety issues and property loss during a fire incident. In practice, manufacturers claim that their video cladding has UL 94 flammability rating certification or equivalency and hence is considered as electrical devices. However, the scope of UL 94 clearly indicates that it does not cover polymeric materials used for building construction, finishing or contents such as wall and floor coverings, furnishings or decorative objects. Furthermore, the results of UL 94 flammability tests are not applicable to materials with thickness exceeding 13.0 mm (0.5 inches), or with surface area exceeding 1 square meter (10 square feet). Currently, knowledge of the fire hazards and risks incurred by the exterior video cladding wall, e.g. the thermal and toxic threat to which the built environment and occupants might be exposed, remains limited in codes and standards.

Identifying Hazards in Building Facades Containing Combustible Components

Matthew Bonner, MSci, Research Postgraduate, Imperial College London; Sigurjon Ingolfsson, ARUP; Susan Lamont, ARUP; & Guillermo Rein, Imperial College London

Fires in high-rise buildings that involve the facade can have disastrous consequences. Rapid vertical fire spread from the outside of a building can prevent safe evacuation and inhibit effective firefighting. This kind of fire has become a particular problem in recent years, with facades incorporating new, potentially combustible, materials. If the fire hazard presented by a facade could be identified and quantified, then it could go some way towards supporting fire engineers and facade engineers in the design process. This work suggests some first steps in this direction, and demonstrates how optimization could be utilized to achieve an effective, performance-based design approach.

Performance Based Design in Support of an Alternative Method for Laundry Chute Ventilation

Steven J. Whitman, PE, Senior Fire Protection Consultant, JENSEN HUGHES

Current laundry chute ventilation shafts for gravity chutes must be vertically oriented, continuous to an elevation above the roof, and have a vent opening with the same cross-sectional area as the chute to be considered code-compliant. However, the occupancy requiring the use of a laundry chute does not always exist on every floor of a building. With the increase in mixed occupancy hotel, multi-family and/or business high-rise buildings, it is often the desire of designers and end users to reclaim space otherwise taken up by the 2-hour rated shaft required by a laundry chute. This paper presents a case study of a performance based approach to the horizontal orientation of laundry chute ventilation.

The work in this paper is based on the deliverable of a project in which JENSEN HUGHES provided fire protection engineering services. This project involved the construction of a new 17-story hotel in Houston, Texas. An FDS modeling analysis was used to compare a proposed horizontally oriented chute vent with the equivalent code-compliant vertically oriented vent under two (2) design fire scenarios. The performance characteristics for the comparison of ventilation methods were 1) volumetric flow rate of gases expelled through the vent to the exterior, and 2) centerline gas temperature within the ductwork. JENSEN HUGHES provided recommendations to mitigate performance differences between the proposed and prescriptive code-compliant orientations, and the Authority Having Jurisdiction (AJH) accepted the analysis as an alternative means of compliance with NFPA 82. The performance-based solution presented in this study has the potential for implementation in other designs and buildings, however the recommendations made were based on the specific design proposed in this project. These recommendations are expanded upon in this paper to suggest further avenues of research which would build on the project findings to substantiate a potential code change proposal.

Fire Engineering Challenges during Redevelopment of Existing Shopping Centers

Alexander Alexandrovski, CEng, Senior Fire Safety Engineer, BCA Consultants (WA) Ply Ltd

A new shopping center development may present a range of challenges to the fire engineer and the design team. These challenges however are multiplied tenfold when dealing with an extension to an existing center or sometimes even a minor refurbishment.

Many existing centers are approaching their "use by date" and create excellent opportunities for redevelopment. Centers are refurbished, expanded horizontally and vertically. Entertainment venues, sports facilities and restaurant precincts are incorporated to provide patrons with experiences that go above and beyond simple shopping. Shopping centers are becoming city hubs where patrons may spend a better part of the day or even a night.

Large interconnected floor areas, atria, long malls, large occupant numbers, reduced number of exits and extended travel distances all create unique challenges and present opportunities for creative and innovative design. Awareness of the conditions that may impact the new works facilitates the design process, generally reduces construction costs, enables holistic fire safety strategies and expedites the approval process.

The challenges with the existing centers redevelopment broadly fall into two categories: challenges with the building legislation and the existing approvals, and design challenges. This paper discusses the challenges a fire engineer may face when developing a fire safety strategy for an existing center. The examples presented in this paper are from Western Australia, though similar challenges are encountered all over Australia, and possibly throughout the world.

A Quantified Risk-Based Framework for Life Safety

IJsbrand J. van Straalen, PhD, Senior Researcher, TNO & Brian Meacham, PhD, PE, CEng, FIFireE, FSFPE, Managing Principal, Meacham Associates

The demand of a risk-informed performance-based approach for fire safety is growing in the Netherlands. Various major incidents have initiated the need for an upgrade of fire safety regulations. All major stakeholders involved have noted that the existing regulations are limited and that a risk-based approach should be developed.

The discussions on the implementation of such an approach show that fire safety engineers mainly think in fire safety solutions. They know how solutions perform in relation to each other in terms of qualitative risks, but they have difficulty determining how a given solution performs regarding a given quantitative risk criterion. To tackle this discrepancy Van Straalen has worked out a framework for the fire safety goal life safety, which links a quantified risk criterion for life safety with a series of well-defined fire safety criteria for the operative requirements ignition of fire, fire development, evacuation and strength of structures. Those fire safety criteria can be related to generally applied fire safety solutions.

With use of the recently developed roadmap by Meacham and Van Straalen a risk criterion for life safety is proposed in this extended abstract and related to the fire safety criteria with use of probabilistic risk analysis (PRA), to be able to calibrate verification methods and fire safety solution given this risk criterion for life safety.

A Holistic Approach to Fire Risk Assessment: How to Combine Bow-Ties of Standard Fire Scenarios to Develop a Creative Yet Robust, Barrier Based, Fire Safety Strategy

Luca Fiorentini, CEO/Executive Director, TECSA S.r.l.

Nowadays performance based approach to fire safety can be considered a specific discipline in fire engineering activities. Performance based approach verifies the fire safety strategy considering specific fire scenarios and the produced negative effects (for occupants, environment and assets or business continuity) in a determined fire dynamics. Fire scenarios should become the basis of the assessment for the evaluation of the fire strategy: given predefined thresholds performance has to be verified being consistent with the fire risk associated with the scenario. Due to the amount of time needed to perform a quantitative assessment of the outcomes of credible and relevant scenarios it is fundamental to start from a precise fire risk assessment. Performance based approaches to fire engineering showed that risk based decisions and fire scenarios are a fundamental element of the fire safety strategy assurance but fire risk assessment has always been a challenging issue. In particular in the latest years, due to the computational possibilities granted by the advances in the information technology sector, performance based approaches have been replaced by the simulation of some scenarios among those considered to be relevant but without any risk assessment or case-based reasoning. This led in the most luck situations in a good reporting, difficult to be updated and without any resilience during time, while it led in the worst situations to three-dimensional cartoons without any real link with the fire and/or with the fire strategy in place. Fire safety strategy should be based on the evaluation of the performance against specific fire scenarios to be identified. Scenarios can be identified using specific standards (e.g. NFPA n. 101) combined with the use of a specific assessment based on the fire safety fundamentals, as those presented in the Fire Safety Concept Tree in NFPA© n. 550, referred to ad "FSCT". Given the paradigm of the "FSCT" for each fire compartment it is possible to judge the completeness of a fire safety strategy and the possibility to face specific identified scenarios in each aspect for the various outcomes (occupant's safety, environment and business continuity or assets integrity). Robust fire strategies are not those implemented by severe and complex studies but are those that really represent the reality and are able to be maintained during time across all the possible modifications. Furthermore the performance should be able to be monitored during time (audited) in order to guarantee a proper level of residual fire risk (acceptable) or to mitigate an increase of risk with alternative measures (technical and organizational). This is an invaluable advantage when you have to identify alternative strategies or new or existing buildings. Alternative solutions can be evaluated taking into account the risk reduction operated by different strategies and by different elements composing the fire strategies themselves and also costs with a modern ALARP approach. Different strategies are based on safety critical elements (SCE) and barriers. So, at the end, from the initial performance based approach, the focus should be put to the fire safety barriers management during time. Complete approach has been supported by an informative system composed by several modules each one dedicated to a specific element of the risk life cycle.

Risk-Informed Airport Fire Engineering Solutions of Operational Continuity

David Charters, PhD, CEng, MSFPE, FIFireE, MIMechE Principal Consultant, Risktec Solutions Ltd. & Alan Sheach, BSc, FIFireE, Principal Consultant, Risktec DMCC

Traditionally new airport terminal buildings have been designed to provide life safety of occupants and protection to the building and contents. Airport operational continuity is also essential for passenger safety and airport efficiency. This paper presents a risk model for the quantification of airport false alarm evacuation disruption and a parametric study to investigate the influence of terminal building area and the benefits of a range of false alarm preventative and mitigation measures.

New Anglo-Polish Methodology for Fire Risk Index Evaluation for Fire Strategies

Dorota Brzezinska, PhD, Lodz University of Technology & Paul Bryant, PEng, Founding Partner, Fire Cubed LLP

Based on the growth of fire safety engineering and performance based solutions, there is a global thirst to develop fire strategy evaluation techniques.

One of the ideas specifically developed for weighting and choosing most appropriate fire safety strategies and systems was a method based upon British Standard Specification PAS 911: Fire strategies – guidance and framework for their formulation. This method is captured in a diagram and identify the eight main elements of building fire safety. It is intended to allow the user of the diagram to identify how each element contributes to the overall fire strategy. As well as allowing the visualization of a fire strategy, it also allows for value analysis as the strategy differs from standard solutions, expected in such building. The idea of it is to allow each of the eight factors to be separately considered and numerically scored, from zero to twenty four, based upon a detailed questionnaire.

As a comparative method, it requires analysis of two strategies: the optimum strategy and the actual strategy. Values received for each strategy allow the calculation of the fire risk index (FRI) and to check if the FRI of the actual strategy is lower or equal to the FRI of the optimum strategy. This score will provide confirmation that suggested actual fire strategy provides a satisfactory of overall fire safety and protection.

Are Verification Methods the Answer to Improved Application of Performance-Based Codes? Be Careful What You Wish For

Peter Johnson, FSFPE, Principal and Fellow, Arup; Nate Lobel, Fire Engineer, ARUP; & Matthew Wright, Chief Technical Officer / Deputy CEO, Fire Protection Association Australia

Building codes are considered living documents which are constantly under scrutiny for change and improvement. This is revealed in the cycles that building codes undergo to maintain currency , (NFPA How the process works, n.d.) (The Key Dates for NCC 2019, 2016). The scrutiny that building codes undergo is often based on maintaining safety, improving efficiency and cost effectiveness of construction, and permitting the use of innovative products, materials, and architecture to meet the evolving landscape of building design. The majority of codes around the world achieve this goal through either a prescriptive basis, a performance based design approach, or offering varying levels of each as an option. For instance, it is generally considered in the fire engineering community that whilst the Building Code of Australia (BCA) technically offers both as a route, it is very much a performance based design driven code with the Performance Requirements being the only legally binding portion of the code, and whilst NFPA 101 provides an equivalency section, it is generally considered a more prescriptive based code.

Australia has had a performance-based building code for over 20 years that allows for performance-based designs, or those that satisfy prescriptive provisions, to meet Performance Requirements. Fire Safety Engineering has thrived under this regime and enabled increased design freedom and supported the growth of the construction industry as a key economic indicator. The performance-based approach allows for fire science to inform decision making and also increases in efficiency of approvals that stray from traditional prescriptive requirements.

Custody of a performance-based code or design associated with it, comes with a responsibility to demonstrate an increased ethical and professional approach. This is due to the subjective and objective decision making required to inform performance-based designs that by their very nature, are unique and can challenge convention. While the Performance Requirements within Australia's National Construction Code (NCC) Building Code of Australia Volume One (BCA)1 remain sound and rarely questioned, there has been a ground swell of concern regarding the lack of consistent administrative checks and balances that should regulate their application. This has extended to include how such administrative requirements ensure adequate robustness of designs and associated documentation and the competency of individuals undertaking this work.

Identifying Implicit Risk in the National Building Code of Canada

Keith Calder, PEng, VP Technical Services – Canada, JENSEN HUGHES

This paper proposes a framework to facilitate the identification of the risk (performance) implicit to acceptable solution requirements in the National Building Code of Canada (NBCC), and facilitate the transition of the NBCC from objective- to performance-based format. The framework is intended to provide the quantitative means to bridge the gap between existing prescriptive requirements and performance objectives. A basic example is provided to illustrate the application of the framework.

Connection Behavior in Contemporary Canadian Buildings Subjected to Real Fires

Matthew Smith, PEng, MASc, Engineer, Entuitive. Toronto, Canada & John Gales, PhD, Assistant Professor, York University. Toronto, Canada

In structural performance-based fire design (PBFD), engineers design a structure to resist realistic fire scenarios demonstrating the desired performance goals analytically. PBFD currently sees varying levels of adoption throughout the world, with its inclusion in projects typically depending on the complexity of the project itself, the construction of the building, and the regulatory environment in which that project exists. This study outlines the PBFD of a contemporary Canadian building that was assessed for a range of realistic design fires including travelling fires, which is a severe and probable fire event in contemporary structures which has received little research attention in Canada. In particular, the paper focuses on the behavior of the connections in the composite steel structure when whole building response is considered. Connections in these real fire scenarios experience very large axial demand which must be considered during design, the magnitude and duration of these axial demands differing greatly depending on the fire considered (standard, parametric and travelling). Regardless of the design approach for a building, understanding and being able to quantify the behavior of the connections for a range of fire scenarios is critical to ensure a resilient structure for extreme fire events.

Fire Dynamics Simulations for Performance-Based Fire Safety Design of Steel Structures in Large Enclosures

Chao Zhang, PhD, Guest Researcher, National Institute of Standards and Technology; Hong-Xia YU, Arup International; & Lisa Choe, National Institute of Standards and Technology

The engineering design practice usually includes fire protection design of steel structures in large volumes. Prescriptive methods in fire codes are based on the concept of fire compartmentation and are not applicable to large volumes. As an alternative, performance based methods are usually adopted, which need sophisticated numerical models to adequately simulate the responses of structures in the design fire scenarios. This paper discussed the application of the Fire Dynamics Simulators (FDS) for performance based fire safety design of steel structures in large enclosure. Recent studies on using FDS to model the localized fire tests on steel columns and steel beams are reported and a case study on using FDS for structural fire engineering design in an airport project at Beijing China was also presented.

Performance-Based Fire Resilience Evaluation for a Tall Building Structure

Jenny Sideri, PhD, Senior Engineer, Thornton Tomasetti

The surge in the construction of tall buildings along with multiple reports of fire-induced failures in these structures during the last few decades highlight the need for evaluation of the sufficiency of prescriptive design methods. This study evaluates the fire resilience of a tall building structure by means of numerical analysis. The objective is to analyze how the structure and its code-prescribed fire protection would actually perform in different fire scenarios. A subsequent goal is to determine whether the fire protection is adequate, or if it could be optimized to improve safety or reduce costs in a performance-based design approach. The study is performed with a combination of computational fluid dynamics (CFD) and finite element (FE) tools that have been validated for fire analysis.

The Case for Performance-Based Design for Fire Safety

Marianne Foley, PhD, MENG, SPER, Principal, Arup

Performance based design comes with challenges; particularly education, regulation and building approvals. But whilst the 'tick box' approach of prescriptive codes is far easier to manage, it is proposed in this paper that the benefits of performance based design far outweigh the negatives. Through examination of the benefits achieved on a range of different project examples, across many different types and uses of buildings, the case is made for performance based design, and indeed for fire safety engineering to be an engineering design profession rather than simply an application of prescriptive code.

Performance-Based Fire Safety Design for Dongao Tunnel

Kuang-Chung Tsai, PhD, Professor, National Kaohsiung First University of Science and Technology & Wei-Ting Chung, PhD Student, National Kaohsiung First University of Science and Technology

The performance-based fire safety design for Dongao tunnel, one 3.38 km tunnel in Su-Hua road, has been conducted in Taiwan. Dongao tunnel was the first one in Taiwan to install water spray system, and a point extraction smoke control system was applied. The integration of water spray system and smoke control system is consequently important. This study used FDS to simulate the fire and smoke behaviors and evaluate whether the design can pass the criteria, including the safety of evacuee, fire fighters, concrete and the risk of fire spread. The items considered for the performance-based design were discussed, including the slope effect, piston effect, traffic jam, external wind effect and relative positions of smoke vents, water mist region and evacuation tunnel. Two fire scenarios were i) a truck incident resulting in 100 MW fire, and ii) two buses accident involving 5 cars causing 100 MW fire. Our simulation results illustrates that the design can pass the criteria with the application of "does" concept when considering the exposure time of radiant heat flux of evacuee and temperature of concrete. Additionally, our results showed that the fire safety performance when both longitudinal ventilation and water spray were used was enhanced than only ventilation system was applied. The most significant effect of water system was reducing the temperature of concrete to prevent the spalling of concrete.

Performance Based Design: Testing of CPVC Sprinkler Piping for Concealed Spaces in a High Rise Historical Building

Noah Ryder, PE, Managing Partner, Fire & Risk Alliance, LLC.

An 86' tall residential building in Chicago built in 1897 and significantly renovated in 1985, defined as a high-rise building per the Chicago Building Code (CBC) was required to undergo a Life Safety Evaluation (LSE) per the CBC. The building has a "U" shape with 6-stories, basement, "cockloft", and penthouse levels, encompassing approximately 24,350 ft2 area per floor. The building is comprised of Type III-B construction (wood joist floor/ceiling assemblies) and as such does not meet the current requirements for height and area limitations as defined in the CBC. As the building was constructed pre-ordinance, it existed without violation. Due to the lack of passive fire protection, the building would not pass the LSE as currently constructed. At a meeting involving the AHJ it was determined that due to the unique nature of this building (date of construction, height of building, construction type) that the building would be required to be equipped with a complete automatic sprinkler system throughout the building, and, therefore, no longer be under the purview of the LSE process.

Due to the historic and aesthetically sensitive nature of the building, it was determined by the building owners that sprinkler piping must be installed concealed, not exposed. An existing combustible concealed space above the plaster drop ceiling assembly was determined to be the location of all sprinkler pipe routing. Due to lower material costs, ease of installation, and minimization of resident impact, the decision was made to utilize CPVC piping for the new sprinkler system.

During survey, it was observed that the combustible construction of the floor/ceiling assembly above the common corridors were enclosed with plaster that is directly attached to the solid wood joists. A plaster drop ceiling assembly was installed approximately 10" below this higher ceiling. These combustible concealed spaces were to be protected with upright sprinklers as required by NFPA 13. These upright sprinklers are required, by the listing of the CPVC piping, for this installation application.

The floor/ceiling assembly configuration above the residential space, however, is comprised of 2x10 solid wood joists that are 16" on center with a wood decking. The drop ceiling below is comprised of a plaster/gypsum that is attached to metal studs. The bottom of the ceiling assembly is approximately 21" below the upper deck. As part of its listing requirements, the combustible concealed space sprinkler is not permitted to be installed within this construction configuration with CPVC piping. Per the requirements of the sprinkler, the upper deck of the solid wood joist construction is to be filled with non-combustible insulation when used in conjunction with CPVC piping. The installation of this non-combustible insulation between the solid wood joists would present a large expense for the condominium association, and therefore, the individual condominium owners of the building. Without the installation of this insulation, the only other listed alternative is to provide steel pipe instead of the CPVC. Again, this would incur a large increase in installation cost due to both higher material costs and complexity of installation.

Using BIG Data for Automatic Fire Alarm System Response Strategies

Bödvar Tomasson, MSc, Fire Eng, Division Manager Fire & Risk, EFLA Consulting Engineers & Björn Karlsson, PhD, Director General, The Iceland Construction Authority

Automatic Fire Alarm Systems (AFAS) are important for initiating the evacuation of people from burning buildings as well as giving the Fire and Rescue Services (FRS) more time for extinguishment actions whilst the fire is in a manageable state. However, automatic fire alarm systems often produce false and/or unwanted alarms, causing considerable costs due to unnecessary fire brigade callouts. We wish to reduce the cost and risk with unnecessary callouts and at the same time increase the likelihood of successful rescue operations. We also want to provide data for fire safety engineering with the aim optimizing design. This can be achieved by identifying, collecting and analyzing relevant data, not only on the sources of false alarms, but also regarding the effect on better information related to real data.

Smoke Management in Detention Facilities

Steven Dannaway, PE, Fire Protection Engineer, Coffman Engineers, Inc.

The recent editions of the International Building Code (IBC) require windowless buildings in Group I-3 occupancies to be protected by an engineered smoke control system designed to maintain a tenable environment in the smoke compartment of fire origin. The unique conditions encountered in detention and correctional occupancies present numerous challenges to implement a smoke control system designed to maintain tenability. In many instances, the smoke control system must be designed utilizing analytical tools such as CFD modeling and a performance-based design framework as detailed in the SFPE Engineering Guide to Performance-Based Fire Protection [1]. Using a recently completed project as a case study, this presentation intends to review key factors that drive the design of smoke control systems in detention facilities, illustrate how analytical tools like the Fire Dynamics Simulator (FDS) can be applied as part of a performance-based design methodology, and raise questions that may help to advance the fire protection engineering design approach in detention facilities.

Walking Speed in Smoke: Representation in Life Safety Verifications

Karl Fridolf, PhD, Technical Specialist, WSP Sverige AB & Daniel Nilsson, PhD, Senior Lecturer, Division of Fire Safety Engineering, Lund University

The gradual transition from prescriptive to performance-based regulations has led to a worldwide development of methods and techniques for designing and verifying the fire and life safety performance of buildings and infrastructure. During, for example, the design of complex underground structures, such as road and rail tunnels, a structured risk assessment method is often adopted within which a number of representative fire and evacuation scenarios are identified, analysed and assessed using advanced calculations. Typically, these include an analysis of peoples' ability to safely evacuate the infrastructure without being exposed to untenable conditions according to the so-called egress time-line model. In practical terms, this means that the required safe escape time (RSET) is compared to the available safe escape time (ASET) for each scenario in more or less independent fire and evacuation calculations or simulations. In addition, a more advanced technique may also be adopted, in which the accumulated dose of irritating and/or toxic gases are compared to the doses resulting in incapacitation or death according to the so-called fractional effective dose (FED) concept.

Beyond ASET vs RSET: Performance-Based Fire and Crowd-Flow Safety Design of Large Scale Stadiums

Yoshikazu Minegishi, PhD, PE, Fire Engineer, Takenaka Corporation & Naohiro Takeichi, PhD, Leader of Life Safety Group, Takenaka Corporation

In most cases of performance based fire safety design, main concern and safety criteria are just the comparison of ASET and RSET, but in the design of the facilities which hold a large number of people, controlling the crowd flow becomes more important. In this paper, we discuss the important aspects of crowd flow design in performance based fire safety design through the actual design example of a large scale soccer stadium in Japan. In particular, 1) care for the upper stand where both evacuees and smoke tend to accumulate, 2) to let evacuees accumulate on flat area like concourse and avoid accumulation on stairs, 3) effective guidance method at outside of the stadium, are discussed.

Practicalities and Limitation of Coupling FDS with Evacuation Software

Daniel Blixt, Senior Consultant, WSP Fire & Risk Sweden & Daniel Rådemar, Fire Protection Engineer, WSP Fire & Risk Sweden

Computational Fluid Dynamics (CFD) allows the available safe egress time (ASET) to be calculated for a design by modelling the fire and smoke movement. An assessment of evacuation movement then needs to be made to estimate the required safe egress time (RSET). Many evacuation software exist, but very few allow a direct coupling of the CFD and occupant movement data. This coupling is advantageous as it allows for visualization and quantification of tenability conditions. However, coupling two different software types is not always straightforward and is still a developing feature in evacuation software.

The emphasis of this paper is on the coupling of evacuation software with Fire Dynamics Simulator (FDS). Pathfinder, STEPS and Evac software were considered. An example geometry based on an underground rail station was used to compare the setup, limitations, advantages and outcomes using the different evacuation software. The Fractional Effective Dose (FED) was used to calculate the RSET for this investigation. This paper provides a reference for other practitioners of specific issues to consider when setting up their own models. It also demonstrates some of the competencies required when coupling FDS with evacuation software that may not be obvious to less experienced practitioners.

Accounting for Uncertainty in Computational Fluid Dynamics Modelling of Fully-Developed Compartment Fires

Vinny Gupta, BEng, MPhil Researcher in Fire Safety Engineering University of Queensland & Jaime Cadena, MSc, BSc, PhD Researcher in Fire Safety Engineering, University of Queensland

Fire modelling range from hand calculations using empirical correlations to Computational Fluid Dynamics (CFD) simulations, along with increasing complexity and uncertainty. The importance of these models lays in support their outputs provide for decision-making regarding fire safety strategies. The study herein explores uncertainties in modelling fully-developed compartment fires with CFD by comparing the selected model outputs against experimental data from a medium-scale fire test. The document includes qualitative and quantitative comparative analyses. This study aims at setting the grounds for practical guidelines to account for the uncertainties when modelling fully-developed compartment fires with CFD.

A CFD Study to Identify Methods to Increase Maximum Velocity of Make-up Air for Atrium Smoke Control

Christine Pongratz, BS, MS, Fire Engineer, Arup

The primary purpose of this study is to develop engineering methods to assess the impact of increased make-up air velocity in atria. The current restriction defined by NFPA 92 states that make-up air must not exceed 1.02 m/s (200 fpm) during the operation of a mechanical smoke exhaust system. The makeup air required for atria during the operation of a mechanical smoke exhaust system may involve large areas of passive openings and mechanical ventilation, all located below the smoke layer. This limitation not only limits creative and aesthetic atria designs but also involves significant costs. Many engineering designers use alternative methods to exceed the limit of the code, claiming that the velocity limit is too restrictive.

Fire Safety Upgrades of Underground Railway Systems

Felix Gamon, CPEng, Accredited Certifier NSW Fire Safety, Consulting Group Leader, Arup

Several major cities around the world have passenger rail tunnels that are approximately 100 years old (e.g. London, Madrid, Sydney). The practice of determining appropriate fire risk mitigation measures for upgrade and improvement of existing rail tunnels is very challenging. Modern codes and standards often cannot reasonably be applied retrospectively to such assets and it is difficult to determine with accuracy the feasibility and cost of potential upgrades.

This paper gives an overview of some of the work we have been doing in Sydney, Australia, to determine feasible, cost efficient and effective upgrades to existing rail assets.
The Sydney metropolitan rail network supports 1 million passenger journeys per weekday and at its heart it includes 26 underground or covered stations connected by tunnels ranging in age from 1924 to 2009.

Some of the key issues with upgrading Sydney's underground rail network to current standards include tunnel cross-sections that are too small to fit tunnel ventilation or raised side walkways, little/no smoke control at stations, lack of choice of egress from platforms with stairs/escalators that typically land at a common concourse, rolling stock that is difficult to get off within a tunnel and some of which doesn't have detection/CCTV/passenger help points.
To upgrade the underground to current standards, even for the relatively small number of underground tunnels and stations in Sydney, would be expected to cost $10bns. Yet only a very small proportion of the network risk (less than 4%) is attributed to fire, which means that these large sums of money might be better spent elsewhere for effective risk reduction or other social benefits.
For example, on average someone falls between the train and the platform edge 6 days per week in Sydney. Most of these are minor injuries or just embarrassing, but occasionally the injury is more serious. But it doesn't make the news. Whereas, injuries from fires on underground rail systems make news headlines, often globally, and cause great concern for passengers. Think of the Washington Metro fire incident in January 2015 in which one person died – and not directly from the effects of fire/smoke.

And also, large fires can result in catastrophic consequences.
So mitigating fire risk in underground rail environments is important, but not at costs that would prohibit other risk reduction measures being implemented.

Fire Safety in Tall Buildings – a London Fire Service Perspective

Kevin Hughes, MBA, BEng (Hons), FIFireE, Managing Director, K.P. Hughes & Associates Limited

There is a consensus that tall building development is here to stay. Cities need to meet the demand for housing and commercial accommodation and with city land plots at a premium across the world, building taller is the commonly accepted answer. Tall buildings are considered to answer many of modern society's needs. They deliver real value back into the local economy by increasing population density. They prevent urban sprawl and provide for all aspects of community diversity.

Assuming iconic positions in a city's skyline they also provide bragging rights. Prosperous cities want the tallest and most architectural stunning tall buildings as a testimony to their technological genius and their place on the world stage.

Tall building designers across the world are motivated by building ever taller and creating multiple use occupancies on ever growing floor plates. "Vertical Village" is a term commonly used to describe tall buildings in which the occupants can live, work and spend leisure time all without ever leaving the building. This is a significant departure from early tall buildings which were simply either all residential flats or commercial office blocks and had largely identical layouts on each floor. The Vertical Village offers both apartments and work spaces along with large open plan recreational facilities such as restaurants, cinemas and swimming pools as well as rooftop sports areas and gardens.

Behind the stunning and beautiful internal architecture of these buildings are the materials, services, systems and facilities that make the building functional, efficient and safe. In order to deliver the ever-increasing aspirations of tall building designers all of these "behind the scene" technologies have had to adapt and develop at a significant pace. Fire safety within tall buildings is no exception. Tall buildings are rarely fully building code compliant, most contain varying degrees of fire engineering.

The application of fire engineering allows professionals to use engineering techniques in a design in lieu of code suggested methods of compliance and be able to demonstrate that these engineering solutions meet the fundamental principles of fire safety and deliver a level of life safety equivalent to or greater than the functional requirements of the building codes. The major benefit of this approach is the greater flexibility afforded the designer in terms of space size, form, function and occupation. However, from a firefighting perspective it often adds to the challenge.

The challenges of tall building firefighting are predominantly defined by lack of access, similar to firefighting in tunnels and basements. Generally, firefighters enter at ground floor level and carry all their equipment up to below the fire floor, establish a bridgehead and then commit crews in breathing apparatus to fight the fire. Tall buildings do not allow multiple points of entry into the building, surrounding a fire, external firefighting and or rescue.

It is because of these physical and tactical limitations that tall buildings are mandatorily provided with fire service access and facilities. Generally, the higher a building is to be built the more firefighting facilities are required.

A Performance-Based Approach for the Design of Engineered Timber in Buildings in the Australian Context

Mario Lara Lederman, PEng, Technical Manager – Fire Safety, Lendlease & Nathan White, PEng, Team Leader – Fire Safety Engineering, CSIRO

Current (and emerging) trends in the built environment highlight that future building design will have a strong focus on sustainability, prefabrication, modulation and complex architectural/structural design. Engineered timber as a construction material has the potential to deliver on these priorities through its sustainable characteristics, processing and handling benefits, aesthetics and structural response. However, gaps in knowledge limit the flexibility of its use and the ability to maximise the benefits of this technology.

In many countries, the use of engineered timber in the construction of buildings is becoming common practise as the technology is adopted and incorporated in building regulations. Australia has embraced the use of engineered timber for structural elements by incorporating prescriptive Deemed-to-satisfy (DTS) solutions in its National Construction Code (NCC). Nevertheless these DTS provisions impose limitations, restricting timber use to certain building classes (residential and commercial), to a maximum height (25 metres), requiring sprinkler protection (regardless of height) and negating the ability to express components (timber structure is to be encapsulated in a fire-protective covering).

In an effort to further understand the fire safe use of engineered timber, Lendlease initiated a research and development (R&D) project aiming to collect the necessary information to expand the application of engineered timber in design and construction by closing existing gaps in knowledge and to support performance-based design. As part of this process, physical testing and experimentation delivered quantitative information to support the design of timber buildings with more design flexibility compared to prescriptive code requirements.

This paper provides an overview of concepts and experimental work being used to support the design of engineered timber buildings in Australia.

The Role of Wood Chemistry in Determining the Charring Rates of Timber under Realistic Fire Conditions

Franz Richter, PhD Student, Imperial College London & Guillermo Rein, PhD, Professor of Fire Science, Imperial College London

We present here an overview of the recent work at Imperial College London on the charring of timber, such as Cross Laminated Timber (CLT), under real fire conditions. CLT is an emerging, promising building material—cheap, strong, and sustainable—with the potential to make high-rise timber buildings reality. However, its behaviour during fire is poorly understood. For structural application, the charring rate of timber can be used to determine the loadbearing capacity. Based on furnace tests and following the standard fire curve, the charring rate is assumed to be one constant valid for all conditions. This simplification is a serious limitation to engineering and performance-based design. Recent work has shown that the standard fire does not represent a realistic fire in large open space floors, such as those present in most new commercial buildings. We investigate here whether the assumption of a constant charring rate holds under realistic fire conditions. For this purpose we developed a detailed model of charring including chemistry, heat transfer, and mass transfer. We study especially the role of chemistry in predicting charring rates for fire safety applications. The chemical model has been developed at the microscale using mg-samples. The heat and mass transfer model has been developed at the mesoscale (Cone-Calorimeter) using kg-samples. The combined charring model was then applied at the macroscale, kg-tonne samples, to predict the behaviour of timber during realistic fires. At each scale, we extensively validate and compare the model to over 80 experiments in total, including the charring rates found during the standard fire. Applying this model to realistic fires shows that the charring rate depends strongly on the fire condition. Hence, the assumption of a constant charring rate does not hold during realistic fires and hinders performance-based design for timber. New tools to evaluate charring during real fires are needed. Work is underway at Imperial College London to develop these tools, and to thereby enable fire engineers to design safer and taller timber buildings in the future.

Performance-Based Design of Fire Safety in High-Rise CLT Buildings

Robert Jönsson, FSFPE, Senior Advisor, Sweco Fire & Risk & Carl Pettersson, Senior Fire Engineer, RED Fire Engineers

The construction industry throughout the world is pushing the development of more buildings constructed completely in timber to a much greater extent than before. The properties of timber, especially Cross Laminated Timber (CLT), bring many new benefits, but fire safety remains a challenge. This abstract focuses on the fire safety issues arising from constructing high rise buildings with CLT volume elements. Six problem areas have been identified and will be addressed. For the purpose of this abstract a high-rise building is considered to be sixteen storeys or more.

The construction of a CLT building is challenging in many ways. More intense fire scenarios can occur if timber finishes are exposed. This has an impact on the capacity of the loadbearing structures, increases the risk for fire spread via openings and also the occupant safety within the fire compartment or adjoining egress paths to the fire compartment. Some of these issues have been addressed in [1] but many challenges still remain.

Another challenge for CLT buildings with a rise in storeys of six above the ground is that the structure and passive fire separations must be designed to withstand vibrations in the structure due to the moving loads inside the building and wind loads. The vibrations are a problem for buildings over eight storeys and for buildings over sixteen storeys, this is a significant problem.

Due to the complexity of high rise CLT buildings and the limited experience that exists within the industry, the fire safety design is time-consuming. The construction time of a CLT building is however, shorter than that of other types of building structures, as is the case for timber buildings in generally. As a timber structure, may shrink over time, especially during the first year, the connections between CLT elements can be compromised and need special attention.

There is still no adopted product standard to achieve conformity of CLT products. This could potentially be a part of the European standard in 2018.

Finite Element Modelling of Post-Tensioned Timber Beams under Fire Conditions

John Gales, Assistant Professor, York University, Toronto, Canada & Hailey Quiquero, MASc Candidate, Carleton University, Ottawa, Canada

In order to implement innovative timber structures globally, performance-based design using numerical models are often required. A model was developed to simulate post-tensioned (PT) timber beams in FEM software ABAQUS and compared to three furnace beam experiments. A sequentially coupled heat transfer – mechanical analysis was developed and validated. The timber was treated as orthotropic both in elasticity and plasticity, and was modelled with temperature-dependent properties. The simulation results showed good agreement with both the thermal results and the mechanical analysis. The thermal results matched the thermocouple readings well and the char depths were predicted to within 4 mm. The failure modes and times were accurately predicted (within 5% accuracy), and the deflection behaviour was reasonably predicted compared to the experimental data.

Green Roof, A Fire Problem?

Daniel Håkansson. Mcs, Fire Protection Engineer, Brandskyddslaget

Increasing request of green roof coverings that not fulfill the formal demands of fire safety in the Swedish building codes initiated a research project on the topic. The aim of the project was to go beyond the prescribed small-scale test method and make a baseline for performance based design. The main conclusion of the project is that given normal Swedish climate the risk of fire spread to and from a green roof is low during most parts of the year.

Situation with Performance-Based Codes and Fire Safety Design in Seven Countries

Brian J. Meacham, PhD, PE, CEng, FIFireE, FSFPE, Managing Principal, Meacham Associates

For the past 30 years there has been a trend toward performance-based building codes (regulations) and engineering design methods. The rationale has included reducing regulatory burden, reducing cost, and increasing the opportunity for innovation in building materials and design, as supported by advancements in technology, data and information. While the early years were characterized by significant change and innovation, the rate of change has slowed. Over the same period, emerging societal pressures and threats have resulted in new regulatory objectives and new requirements for buildings. This has created new challenges for the regulatory, design and enforcement communities. Furthermore, some level of regulatory system failure has been observed in several countries. In order to address these issues and challenges, it appears that some things will need to change. To better understand the current environment in countries with performance-based systems, and to begin to identify potential changes to performance-based building regulatory structures and the practice of performance-based analysis and design, a study of the situation was undertaken in seven countries: Australia, Japan, the Netherlands, New Zealand, Scotland, Spain and Sweden. To narrow the study, the focus was on regulatory provisions and design for fire. In addition, an online survey was conducted to obtain broader insight regarding the global situation with fire safety engineering. More than 400 persons responded from some 40 countries, with sufficient data from six countries to indicate trends. This presentation will overview some of the key issues identified from the research and the survey.

Fire Safety Engineering and Building Information Modelling--Now and in the Future

Andrej Cebela, Fire Engineer, Arup & Judith Schulz, Dipl.-Ing. CEng MEFireE MSt (Cantab), Associate Director, Arup

The building design process is changing rapidly, because of increasing computing power, new tools becoming available, which in turn change workflow processes. Many governments are mandating changes in how buildings information is handled and delivered in order to create:

"Significant improvements in cost, value and carbon performance through sharable asset information."

For example, in the UK, since 2016, the government requires that public sector projects demonstrate a minimum level of compliance with building information management (BIM) processes.

Why does this matter for fire safety and fire engineers? There are two reasons for this:

1. Because fire safety must not be compromised by the drive for greater efficiency, and ever increasing speed of design and construction. To do this, it must be clear what is required and who is responsible for delivering a fire safe building, throughout the entire building project cycle, and across the many disciplines that play a part in delivering fire safe buildings. It will require a new way of working, new processes and new tools.
2. Because the owners and operators of buildings must understand how their building works in the event of a fire, so they can safeguard those in the building, and also fire fighters doing their job. In the UK, the Building Regulations require that fire safety information is made available to the person responsible for the building at the end of a project so they can operate and manage their building safely.

"Regulation 38 requires that, where building work involves the erection or extension of a relevant building, or a relevant change of use of a building, fire safety information shall be given to the responsible person at the completion of the project or when the building or extension is first occupied."

At the moment, in our opinion, there is much room for improvement in this area. What should be provided as part of this pack of 'fire safety information' is defined in statutory fire safety guidance in the UK.

How this fire safety information is provided, and who is responsible for which part of this fire safety information pack in the design / construction process is not defined; and there is no guidance available for this in the UK at the time of writing. After the tragic fire at Grenfell in London which killed 71 persons, how fire safety is regulated, delivered and managed is under close scrutiny and review in the UK [7]. We do not know what the future may hold.

However we want to share the findings from our research at Arup into the opportunities and the challenges that arise when considering fire safety in the BIM process. This paper describes a new workflow process that we have trailed on projects, and sets out the basic necessities we need to embrace if we want fire safety to be part of a digital future.

Smart Building Systems, Real-Time Data Collection and the Use of a Hierarchical Temporal Memory Continuous Learning Algorithm for Fire State Determination

Noah Ryder, PE, Managing Partner, Fire & Risk Alliance, LLC & Elizabeth Weckman, PhD, Professor, University of Waterloo

Fire remains a costly event worldwide even with significant advancements in fire detection and protection systems. The total cost of fire in the U.S. has been estimated to be as high as $350 billion or 2.5% of the U.S. gross domestic product (including monetary equivalents for deaths and injuries). Fires are pervasive, yet anomalous events; the probability of a fire occurring in any given structure during its lifetime is relatively low. Yet, the unforeseeable nature of fire, and its ability for rapid growth, requires timely sensing and transfer of useful information for effective mitigation (prevention or response). The greater the delay in sensing a fire, the larger the potential loss. Therefore, in order to advance the state of fire detection and response, fire signatures, as discerned by a wide range of sensor typologies, must be better characterized and understood.

Recognition that a fire is an anomalous condition suggests that there is a potential opportunity to leverage the increasing number of sensors and real-time data that are available in many structures and, over time, to use signals from them to detect signatures that are directly related to the anomalies characteristic of fire events. Using continuous data-streams to identify such anomalies, i.e. fires, has very practical and useful applications, especially if additional information on the quality of the data or size of the event is available.

For the purposes of this study an anomaly is defined as a point in time where the observed behavior of a system is unusual and significantly different from past behavior, thus indicating a condition that at a minimum requires more investigation, but alternately is a fire. Anomalies may be either temporal or spatial. Temporal anomalies occur when the value of interest is within the normal range regarding magnitude but not within the context of when it was observed. For example, the indoor air temperature may change from 20◦ C to 25◦ C. If this change occurs over one minute, this is likely a temporal anomaly, whereas the same change over an hour may not be an anomaly. In a similar fashion, spatial anomalies occur when the observed values fall outside of the normal range for a given volume. An indoor temperature of 60◦ C is an example of a spatial anomaly.

The detection of an anomaly in a real-time data stream is particularly challenging as the system must be able to collect and process the data and output a meaningful decision in real-time rather than making repeated passes through existing data sets to come to an informed decision. Because of the quantity and complexity of data collected there may be little opportunity for human intervention. As a result the system will optimally operate in an unsupervised environment in which manual manipulation of parameters is not necessary.

Taking a Performance-Based Approach to the Protection of a Membrane Roof Aircraft Hanger--A Case Study

Craig Vesely, PE, Fire Protection Department Facilitator, Affiliated Engineers, Inc. & Mark Fessenden, Director, Industry Relations, Johnson Controls

Sometimes real-world projects simply do not align with prescriptive standards. This case study will discuss a project where performance based design was used to address venting, detection, pump pressure, and wastewater issues in the planning, design, and testing in a Membrane Roof Aircraft Hangar protected with a high-expansion foam system. The presentation will discuss testing at Underwriters Laboratories Inc. (UL) to address a critical design element and will include footage of dramatic testing exercises proving out the appropriateness of the concept.

The Birmingham Gateway Project- Managing Construction Fire Safety within Highly Complex and Densely Occupied Infrastructure Projects

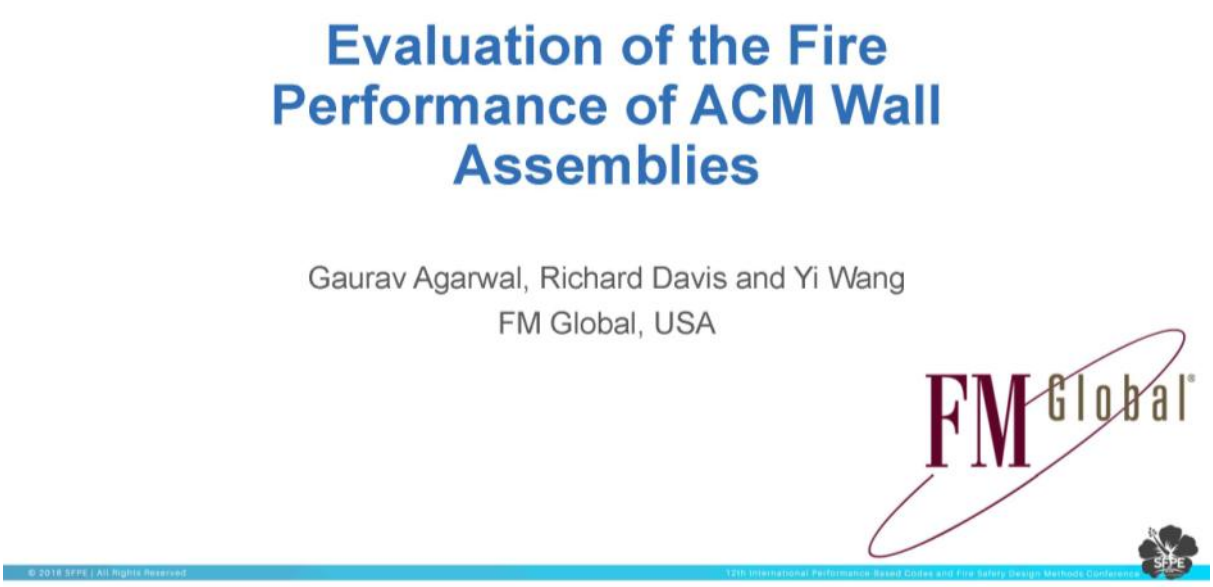
Reece Walker, BEng, Senior Fire Engineer, Arup

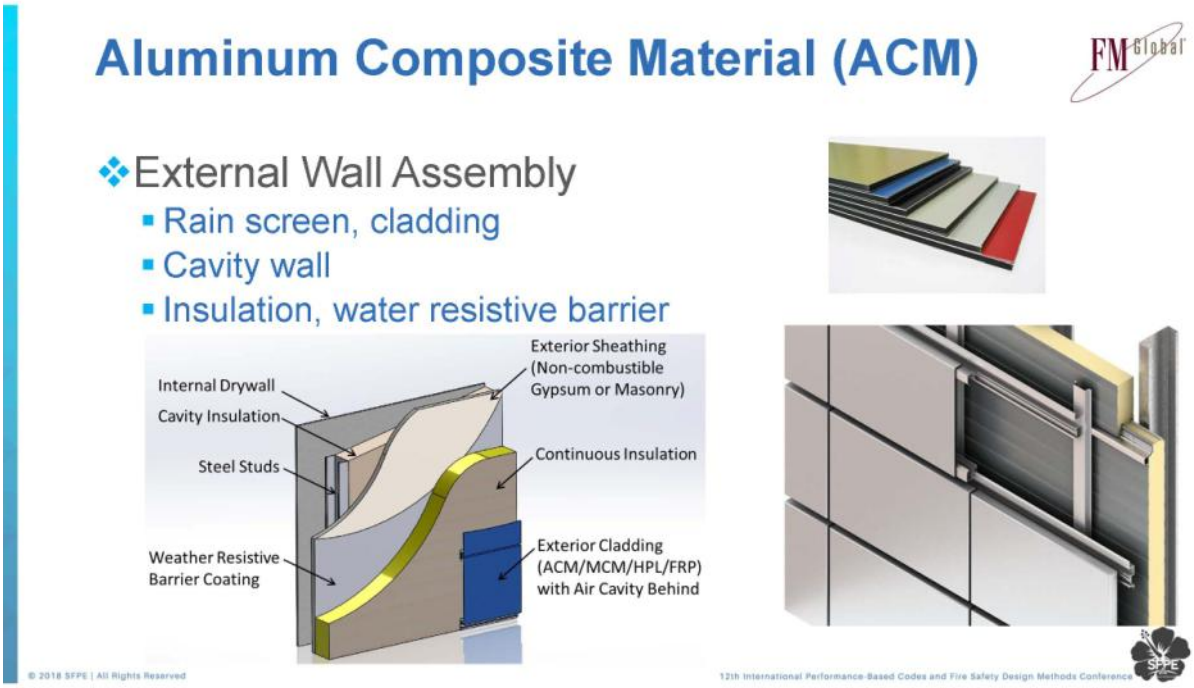
As general engineering design and construction methods have made great advancements in the past 30 years, so too has fire engineering design. The integration of fire engineering in the early stages of projects has allowed for the construction of new, innovative, uncluttered and appealing rail infrastructure across the world. What we have seen over recent years is the need for refurbishment and renovation of existing rail infrastructure, as the costs associated with re-directing/providing alternative rail services far out-weighs the re-design, demolition and renewal of these existing structures.

In September 2015 Arup were part of a project delivery team who completed a major rail infrastructure project in the UK. Arup fire engineers were permanently based on site throughout the 5 year construction programme to provide project fire safety advice and delivering over 400 risk assessments. This paper describes how fire engineering was pivotal to the entire construction project and fundamental to the work continuing within a fully operational Station and Shopping Centre environment outlining the management processes and procedures which were implemented to safely manage a Station which was operating with over twice the passenger numbers it was designed for.

附錄 4 研討會簡報資料

- **ACM** 牆組件的防火性能評估





Grenfell Tower, 2017

- London, UK
- June 14, 2017
- 24 story
- 71 Casualty
- Refrigerator
- ACM-PE

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Wooshin Golden Suites Fire, 2010

- Busan, South Korea
- Oct. 1, 2010
- 38 story
- Electrical
- No casualty
- ACM-PE

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The Address Hotel, 2015

- Dubai, UAE
- Dec 31, 2015
- 63 story
- Electrical
- No casualty
- ACM

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Torch Tower, 2015, 2017

- Dubai, UAE
- Aug 4, 2017
- 79 story
- Cigarette
- No casualty
- ACM

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The Water Club, 2007

- Atlantic City, USA
- Sep. 23, 2007
- 43 story
- In construction
- Hot work
- ACM-PE

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How to Prevent Tragedy Again

- Building code debate and scrutinization
  - Combustible material
  - Fire testing requirement
  - Exceptions
  - Engineering judgement in lieu of testing for components exchange

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Scope and Outline

- Review of fire hazard and standard fire tests
- Present wall assembly tests conducted with ANSI-FM 4880
  - 7 assemblies
  - Parallel panel test
- Comparison with other tests

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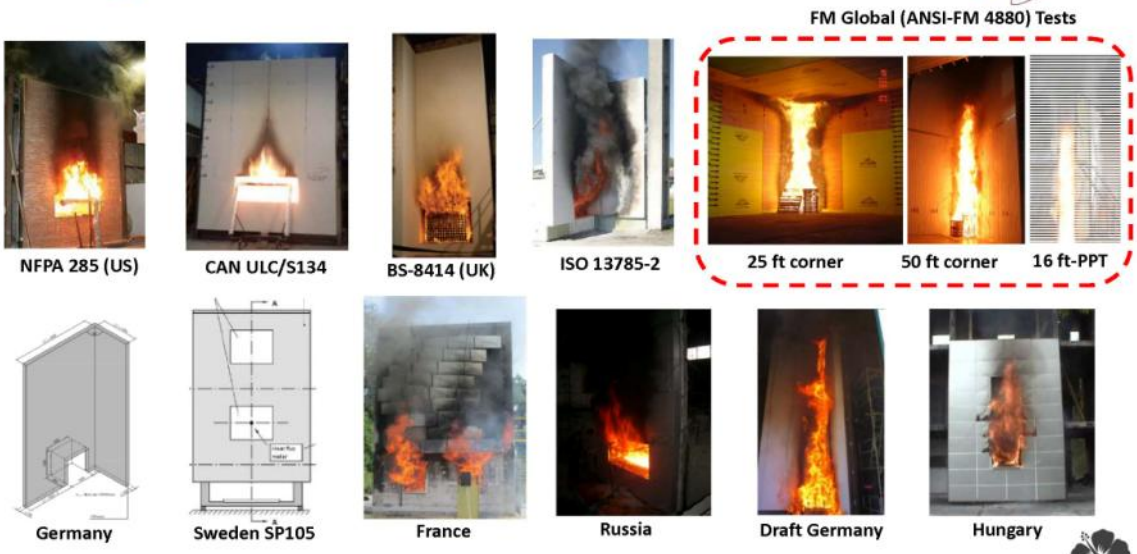
Large-scale Fire Tests for Wall Assembly



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Façade Fire Scenarios

1. Post-Flashover interior fire
   - Spill plume through windows
2. Exterior fire
   - Dumpster fire, storage …
   - Re-entrant corner
3. Cavity wall fire

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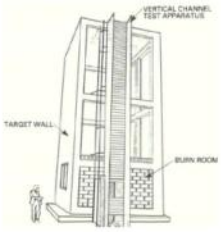
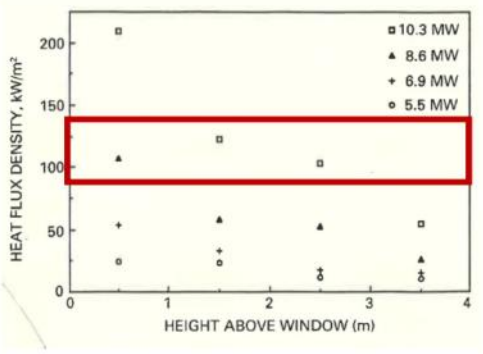
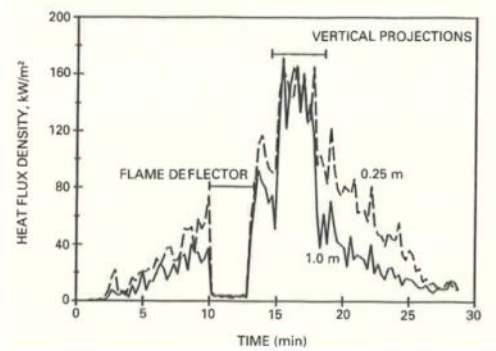
Fire Heat Flux Measurement



- Oleszkiewicz 1990: Heat Flux > 100 kW/m^2





Oleszkiewicz, "Fire Exposure to Exterior Walls and Flame Spread on Combustible Cladding", Fire Technology, 1990

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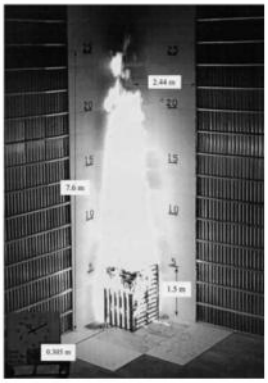
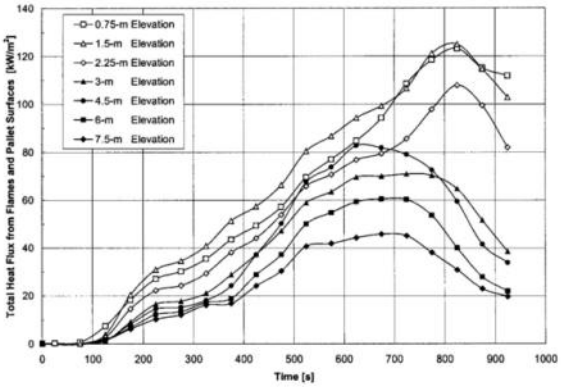
Fire Heat Flux Measurement

- Alpert & Davis 2002: wood crib fire in corner: >100 kW/m²





Alpert & Davis, "Evaluation of Exterior Insulation and Finish System Fire Hazard for Commercial Applications", J. Fire Protection Eng., 2002

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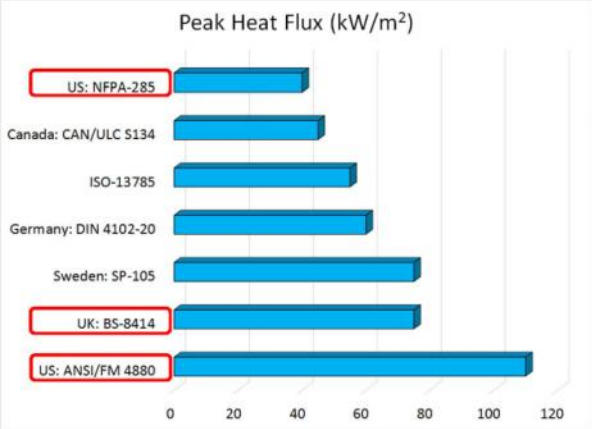
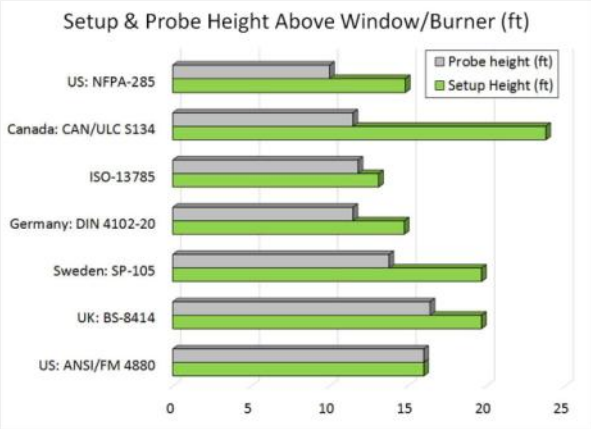
Large-scale Fire Tests - Comparison





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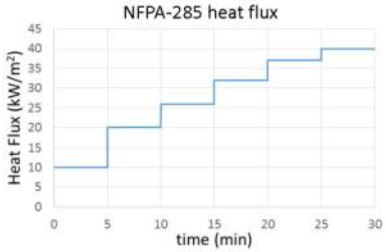
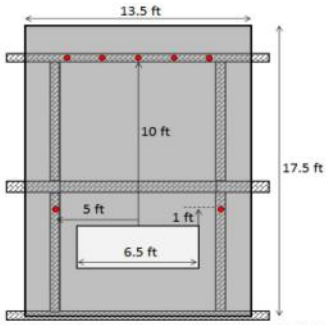
NFPA-285 (Adopted in IBC)



- Peak heat flux to wall: ~40 kW/m²
- Two propane burners: 1300 kW
- Pass criteria
  - Max 10 ft vertical propagation above window
  - Max 5 ft horizontal propagation from centerline
  - Max temperature in
    - insulation (750 F), in cavity/exterior (1000 F)



• TC locations for vertical and horizontal failure propagation

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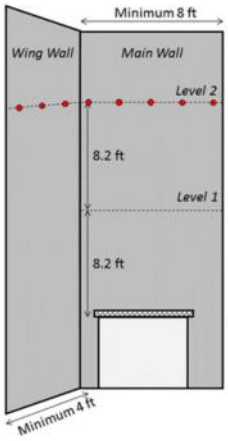
BS-8414 (BRE, UK)

- Peak heat flux to wall: ~75 kW/m²
- 1.5 m³ wood crib
- 26 ft x 8 ft x 4 ft
- Pass criteria
  - Max temperature in exterior/cavity/insulation at 16 ft above window is 1110 F (600 °C above ambient)



• TC locations for monitoring vertical propagation failure

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ANSI/FM 4880

- Peak heat flux to wall: > 100 kW/m^2
- 25-ft and 50-ft corner tests
- 16-ft PPT
  - Correlated with corner tests

25 ft corner test
Since 1970s

50 ft corner test
Since 1990s

16 ft PPT
Since 2000s

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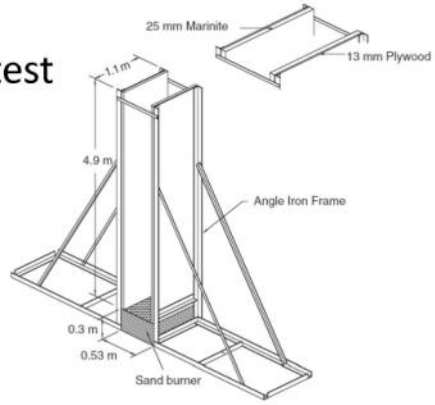
16-ft Parallel Panel Test (ANSI/FM 4880)

- Nam and Bill, 2009
- Intermediate scale: correlate corner test
- 16 ft x 3.5 ft panels, view factor
- 360 kW gas burner
- Peak heat flux >100 kW/m2
- HRR as criteria: 5 MW calorimeter
  - 1100kW
  - 830kW



Nam and Bill, "A New Intermediate-scale Fire Test for Evaluating Building Material Flammability", J. Fire Protection Eng., 2009

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Correlation between PPT and Corner Test

- View factor
- Sand burner
- Same heat flux level
- HRR

$$X_{PMax} = \alpha \dot{Q}'_{ChMax}{}^{2/3}$$

Table 2. Fire propagation correlation between the 25-ft corner test and parallel panel test.

	Fire propagation?		
	25-ft corner test	Parallel panel test ($\dot{Q}_b = 360$ kW)	
Material	Flames along 11.6 m horizontal eave	Reached Q_{ch} = 1125 kW?	Max vertical visual flame propagation
19 mm PVC	Exceeded 11.6 m	Yes in 3 minutes	4.9 m
6 mm PVC	Exceeded 11.6 m	Yes in 2.7 minutes	4.9 m
254 mm polystyrene foam core panels with inert facing	Exceeded 11.6 m	Yes in 4 minutes	4.9 m
19 mm FR-Plywood	5.5 m	No in 20 minutes $(HRR)_{max}$ = 853 kW at t = 109 s	2.4 m
13 mm FR-Plywood	7.0 m	No in 15 minutes $(HRR)_{max}$ = 960 kW at t = 390 s	3.4 m
6 mm FR-Plywood	9.8 m	Yes in 2.7 minutes	4.9 m
76 mm polyurethane foam core panels with steel facing	6.1 m	No in 15 minutes $(HRR)_{max}$ = 513 kW at t = 88 s	1.8 m
2-mm fiberglass reinforced melamine with inert facing	5.2 m	No in 20 minutes $(HRR)_{max}$ = 543 kW at t = 91 s	3.7 m

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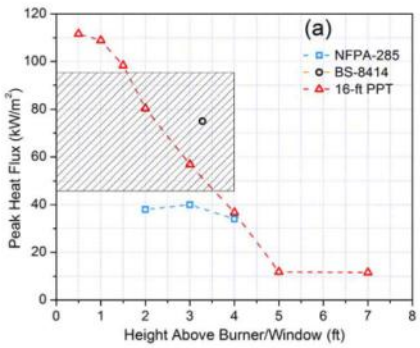
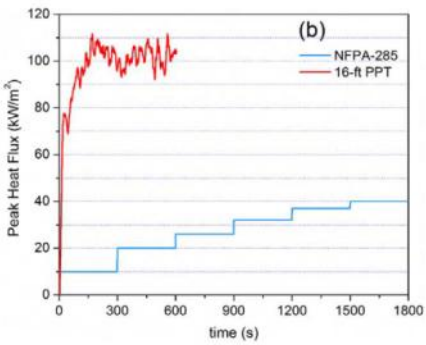
Fire Tests Comparison – Heat Flux



NFPA-285 heat flux is lowest



Slow increase of peak heat flux in NFPA-285

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Fire Tests Comparison – Failure Criteria

Test	Peak Heat Flux	Criteria for Fail
16 ft. PPT	~ 100 kW/m²	Peak HRR > 1100 kW
BS-8414	~ 75 kW/m²	Temperature at 16 ft height > 1110 °F
NFPA-285	40 kW/m²	Temperature at 10 ft height > 1000 °F

Approval Installation Height ↓	Test Criteria ↓
Unlimited height	Peak HRR ≤ 830 kW
50 ft	830 kW< Peak HRR ≤ 1100 kW

*HRR – Heat Release Rate
Rate of energy release in fires

- Global measurement of fire performance.
- Objective and Repeatable.
- Correlated to peak fire propagation height in PPT.

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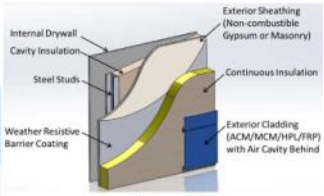
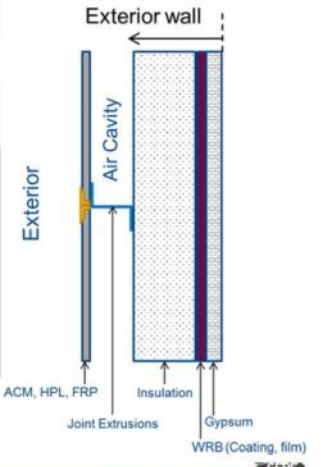
Tested Assemblies

Test #	Exterior Sheathing	WRB	CI	Air Cavity	ACM
1	Gypsum	Yes	--	0.2 inch	PP-core
2	Gypsum	Yes	PIR1 (2 in)	1.2 inch	PP-core
3	Gypsum	--	--	2.0 inch	PE-core
4	Gypsum	--	--	2.0 inch	FR-core
5	Gypsum	Yes	--	2.0 inch	FR-core
6	Gypsum	Yes	PIR1 (2 in)	2.0 inch	FR-core
7	Gypsum	Yes	PIR2 (2 in)	2.0 inch	FR-core





PP – Polypropylene
FR – Fire Retardant
PE – Polyethylene
PIR– Polyisocyanurate
WRB – Water Resistive Barrier

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Tested Assemblies

Test #	Exterior Sheathing	WRB	CI	Air Cavity	ACM	NFPA 285
1	Gypsum	Yes	--	0.2 inch	PP-core	Passed
2	Gypsum	Yes	PIR1 (2 in)	1.2 inch	PP-core	Desktop Ass.
3	Gypsum	--	--	2.0 inch	PE-core	Failed
4	Gypsum	--	--	2.0 inch	FR-core	Passed
5	Gypsum	Yes	--	2.0 inch	FR-core	Passed
6	Gypsum	Yes	PIR1 (2 in)	2.0 inch	FR-core	Desktop Ass.
7	Gypsum	Yes	PIR2 (2 in)	2.0 inch	FR-core	Desktop Ass.

PP – Polypropylene
FR – Fire Retardant
PE – Polyethylene
PIR– Polyisocyanurate
WRB – Water Resistive Barrier

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Desktop Assessment – Quote

- "Based on the results of these tests and my experience with the NFPA 285 fire test, it is my judgment that the various configurations of exterior walls described in the attached tables will meet the performance requirements of NFPA 285."
- "Use any Metal Composite Material system that has been successfully tested by the panel manufacturer via the NFPA 285 test method. Any standard installation technique can be used."

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Assembly Prep Example

Gypsum and WRB

Insulation

Joint system & ACMs with air cavity

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Assembly Prep Example

Central Vertical/Horizontal Joints

16-ft PPT

- 16 ft x 3.5 ft panels
- 360 kW fire source
- Heat flux: >100 kW/m^2
- Placed under 5 MW calorimeter

- Approval Criteria:

Approval Height	Test Criteria
50 ft	830 < HRR ≤ 1100 kW
Unlimited height	HRR ≤ 830 kW

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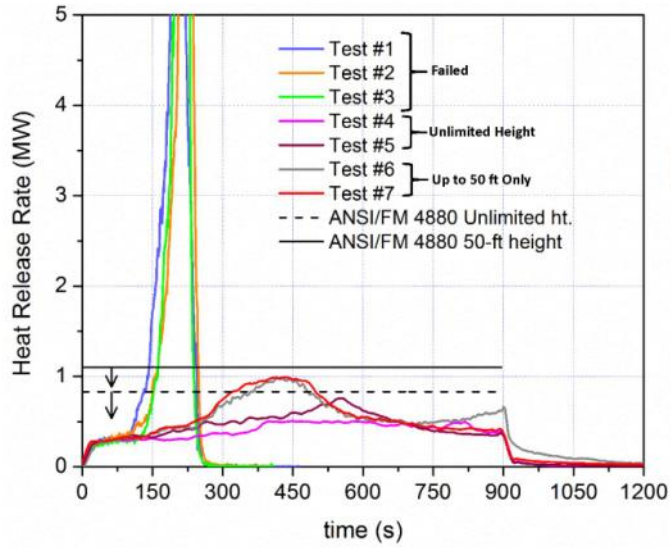
Heat Release Rate



Categorize fire performance:

- Unlimited Height
- Up to 15.2 m
- Very bad performers

Test #	Assembly
1	PP-Core → WRB → Gypsum
2	PP-Core → PIR1 → WRB→ Gypsum
3	PE-Core → Gypsum

Test #	Assembly
4	FR-Core → Gypsum
5	FR-Core → WRB → Gypsum
6	FR-Core → PIR1 → WRB → Gypsum
7	FR-Core → PIR2 → WRB → Gypsum

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Unlimited Ht. vs. 50-ft vs. Failed Assemblies

Unlimited Height
HRR ≤ 830 kW
Burnt height < 8 ft

50-ft limited height
830 < HRR ≤ 1100 kW
8 ft < Burnt height < 16 ft

Failed
HRR > 1100 kW
Burnt height > 16 ft

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Unlimited Ht. vs. 50-ft vs. Failed Assemblies

Unlimited Height
HRR ≤ 830 kW
Flame height < 8 ft

50-ft limited height
830 < HRR ≤ 1100 kW
8 ft < Flame height < 16 ft

Failed
HRR > 1100 kW
Flame height > 16 ft

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Comparison with NFPA-285 and BS-8414

Test #	Exterior Sheathing	ANSI/FM 4880	BS-8414	NFPA-285
1	PP-Core → WRB → Gypsum	Fail	Not tested	Pass (tested)
2	PP-Core → PIR1 → WRB→ Gypsum	Fail	Not tested	Pass (desk top)
3	PE-Core → Gypsum	Fail	Fail	Fail
4	FR-Core → Gypsum	Pass Unlimited Height	Pass	Pass (tested)
5	FR-Core → WRB → Gypsum	Pass Unlimited Height	Not tested	Pass (tested)
6	FR-Core → PIR1 → WRB → Gypsum	Fail Unlimited ht. Pass 50 ft ht.	Fail (6 inch PIR)	Pass (desk top)
7	FR-Core → PIR2 → WRB → Gypsum	Fail Unlimited ht. Pass 50 ft ht.	Fail (6 inch PIR)	Pass (desk top)

- Heat flux of ANSI/FM 4880 and BS-8414 higher than in NFPA-285

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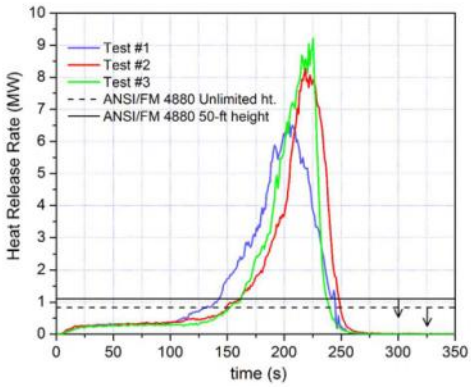
PP and PE-ACM Comparison



Test #1
NFPA-285 Passed

Test #3 (Grenfell like)
NFPA-285 Fail

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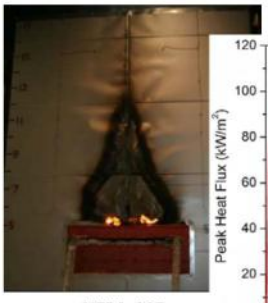
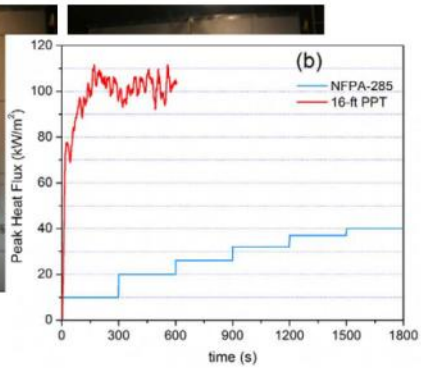
Different Evaluation in Different Tests

FM 4880



NFPA-285



Test #	Exterior Sheathing	WRB	CI	Air Cavity	ACM
1	Gypsum	yes	--	0.2 inch	PP-Core

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Summary

- Evaluated ACM Cladding assemblies using 16' parallel panel (PPT) tests
  - 7 assemblies evaluated, covers typical materials and configurations
    - Clearly differentiate good vs. bad assemblies
    - ACM can be the major fire source
  - Compared with test results from NFPA 285, BS 8414
    - Different evaluation results mainly due to different heat flux levels and time history in the tests
    - NFPA-285 passed assemblies demonstrated high fire hazard in PPT test

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Conclusion and Future Steps

- 16' PP tests are cost effective and robust for evaluating façade assemblies
  - FM external technical report
  - http://www.fmglobal.com/research-and-resources/research-and-testing/research-technical-reports
- FM Approvals Standard 4411 updated
  - "Approval standard for cavity walls and rainscreens"
  - Revision allows ACM systems to be evaluated

FM Approvals

Approval Standard
for
Cavity Walls and Rainscreens

Class Number 4411

March 2018

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Acknowledgement

- Sergey Dorofeev
- JC (John) Harrington
- Tom Roche
- Lou Gritzo
- FM Global Research Campus Staff

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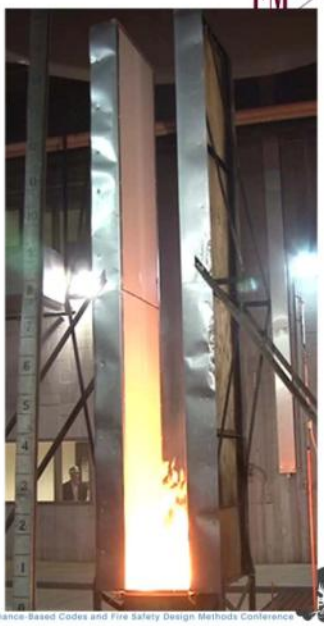
Thank you!

Questions?



Grenfell-like ACM fire:
PE-Core ACM → PIR1 → WRB→ Gypsum

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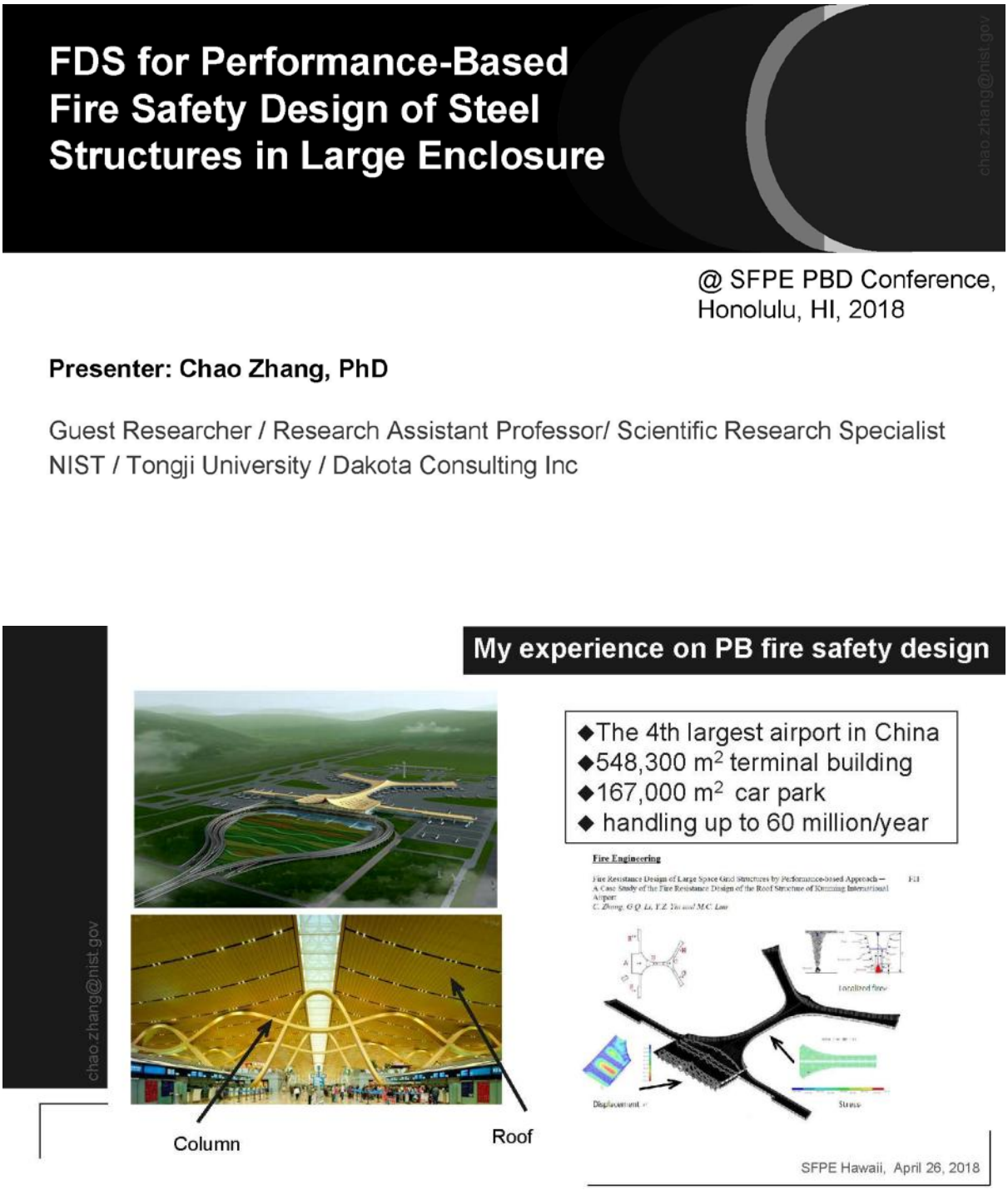
- 應用 **FDS** 進行大型鋼結構外殼性能式火災安全設計研究



My experience on PB fire safety design

The airport features an innovative 'ribbon' steel structure.

Performance-base fire engineering

Arup also developed a performance-based fire engineering design strategy for the iconic

"has been recognized internationally for setting new standards of sustainability, efficiency and safety"

INVEST IN ARUP

3185 Fire resistance design of large space grid structures

Project Overview

Continuation

Aim

To solve the fire resistance design problem of large space grid structures. Two main subjects will be investigated, which are, 1. Temperature analysis of unprotected and protected steelworks in large space fire. 2. Effect of thermal expansion of adjacent structures on fire resistance of steel members in grid structures. By theoretical derivation and FEA simulation, while by collabration and analysis of prior works relating to this subject, mainly the following aspects will achieve , 1. A proper

FINANCIAL YEAR	2008/09
SPEND TO DATE	£208
SPEND TO DATE	2%
STATUS	Closed
LAST UPDATED	05 Nov 2009
FUND	DTF (investment)
SUB-FUND	Ext Coll Res - East Asia
INVESTMENT AREA	Fire
PROJECT MANAGER	Chao Zhang

I left Arup to study for Ph.D degree in Tongji U

chao.zhang@nist.gov

My experience on PB fire safety design

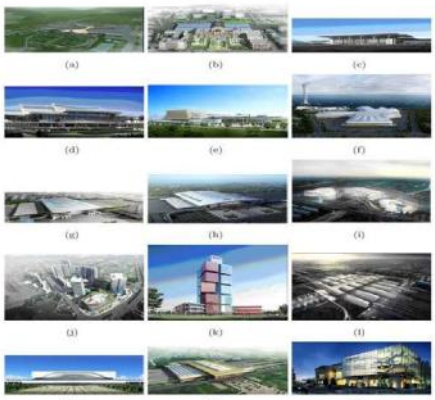
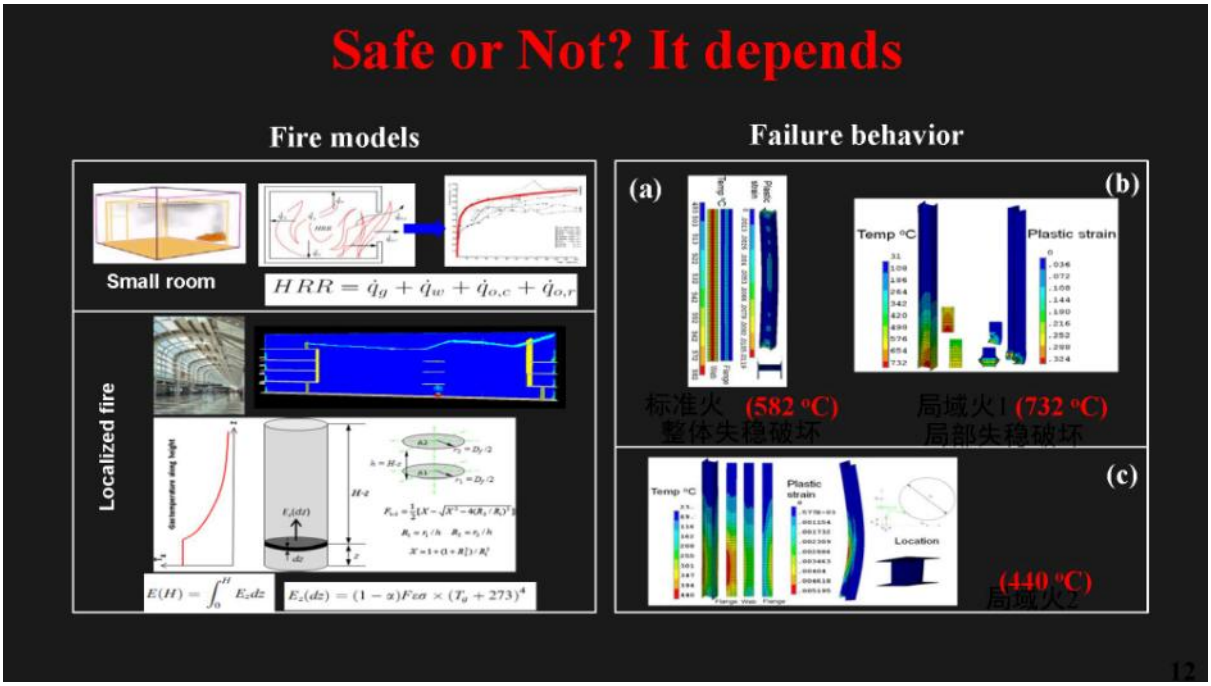


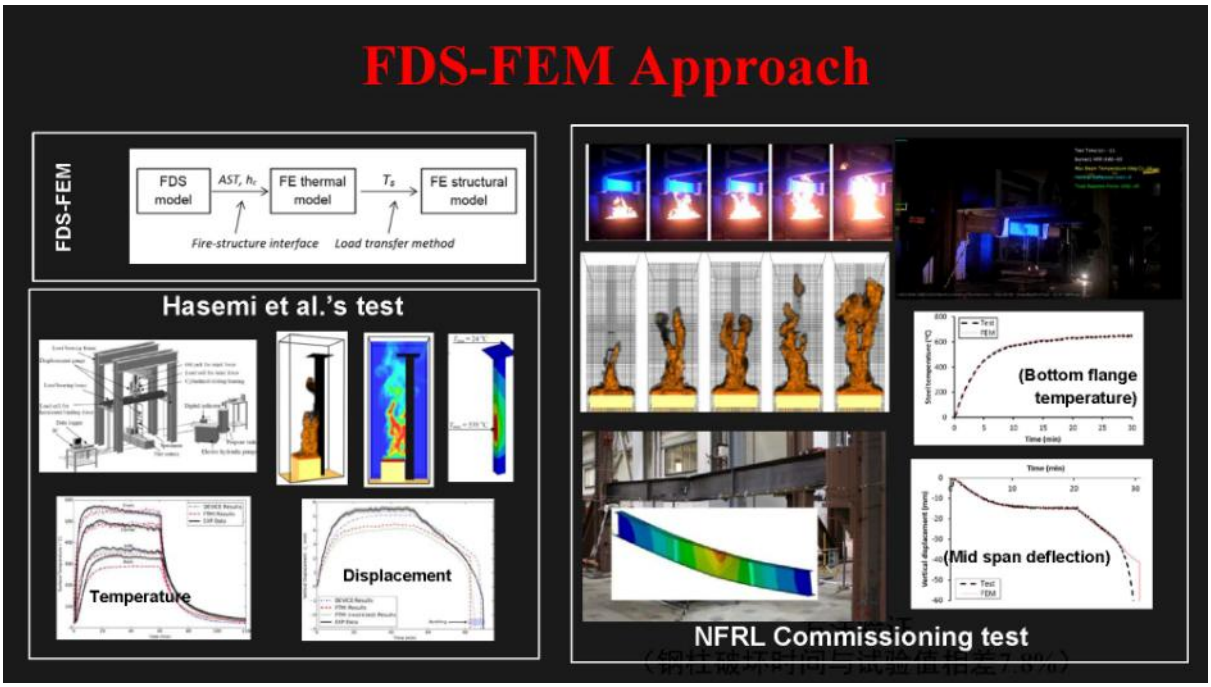
Figure 1: (a)Kunming International Airport, 2008©Arup; (b)Hankou railway terminal, 2009©TJ;(c)Taiyuan north railway terminal, 2009©TJ; (d)Xiamen west railway terminal, 2008©TJ; (e)Shanghai Hongqiao Interchange Railway terminal, 2008©TJ; (f)Hainan international convection and exhibition center, 2009©TJ; (g)Chengdu east railway terminal, 2009©TJ; (h)Hangzhou east railway terminal, 2009©TJ; (i)Shanghai Aquatic Sports Centre, 2009©Arup; (j)Ningbo Plot 5 Capital Plaza, 2008©Arup;(k)Suzhou Logistic Building, 2008©Arup; (l)New Guangzhou railway terminal, 2008©Arup; (m)New Dalian railway terminal, 2010©TJ; (n)Nanjing south railway terminal,2009©TJ; (o)Hangzhou Huning Plaza, 2010©HJA

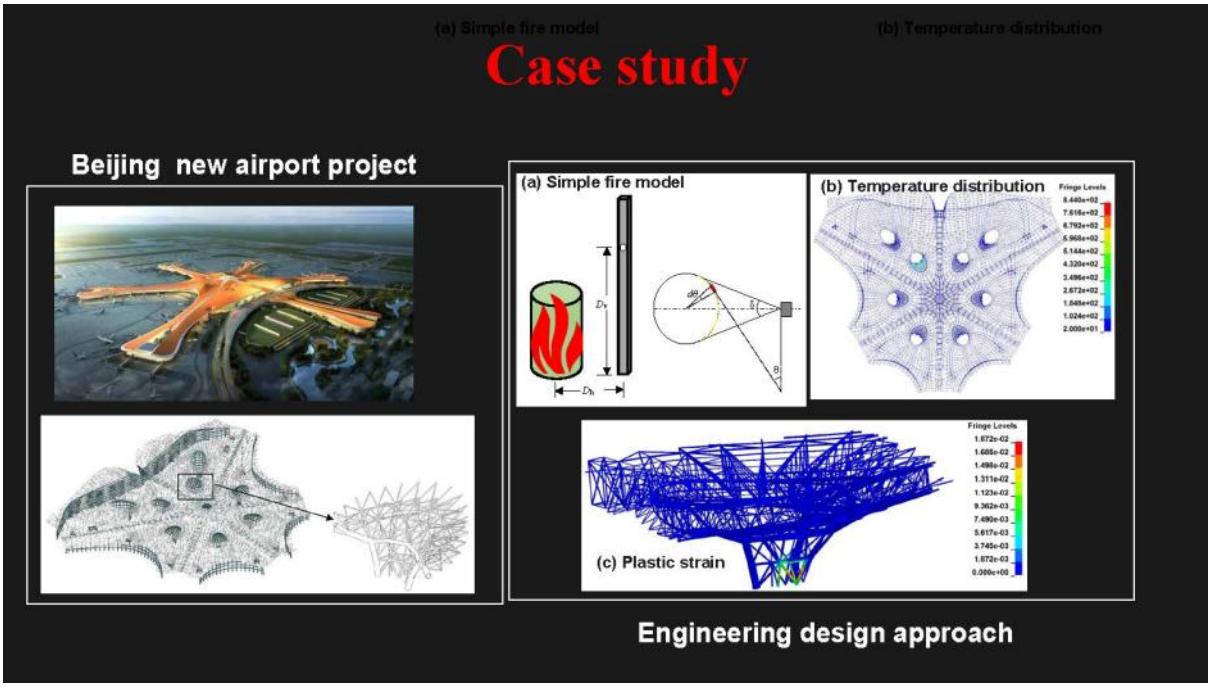
- ◆Participated in PB fire safety design of more than 20 industrial projects in China
- ◆Simple fire models are mostly used in calculation
- ◆Effect of thermal gradient in structural members mostly ignored
- ◆Fire protection totally removed or reduced in some cases

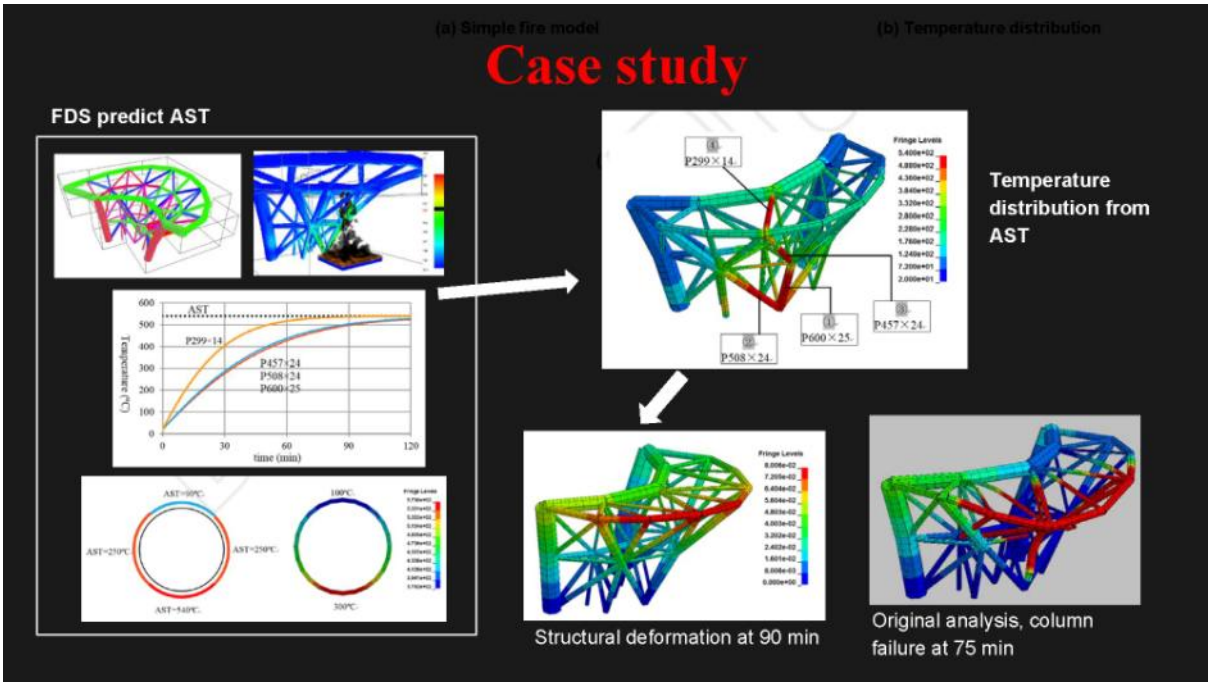
Safe or not?

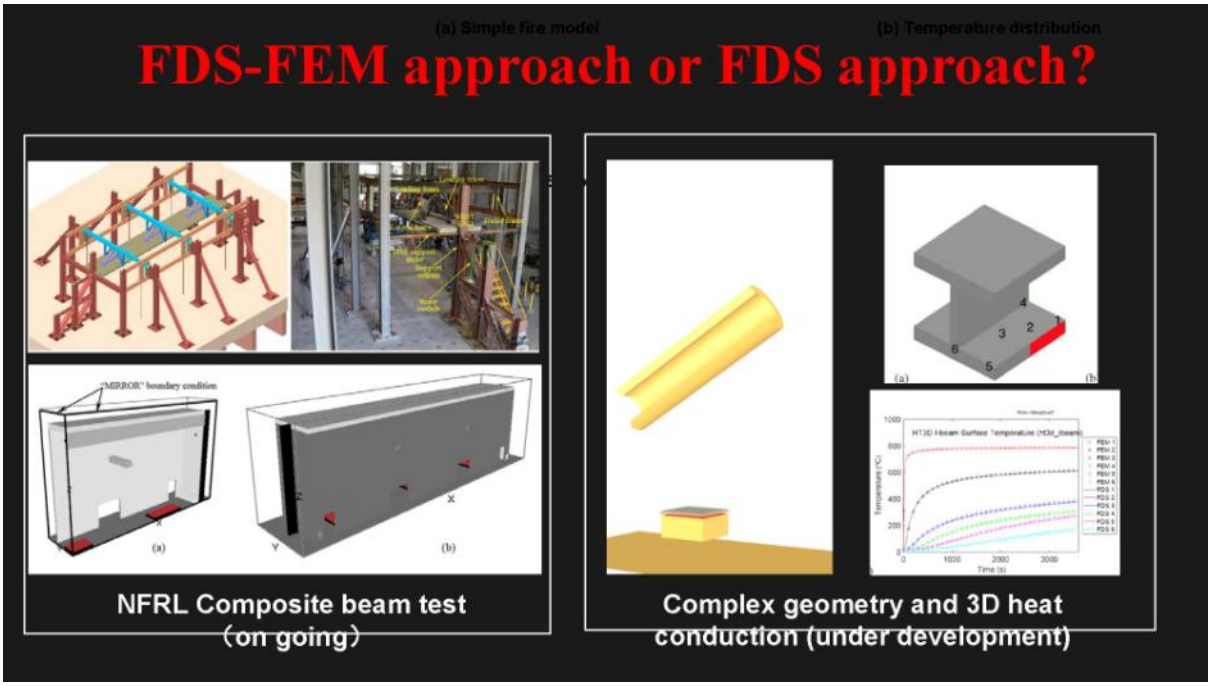
chao.zhang@nist.gov

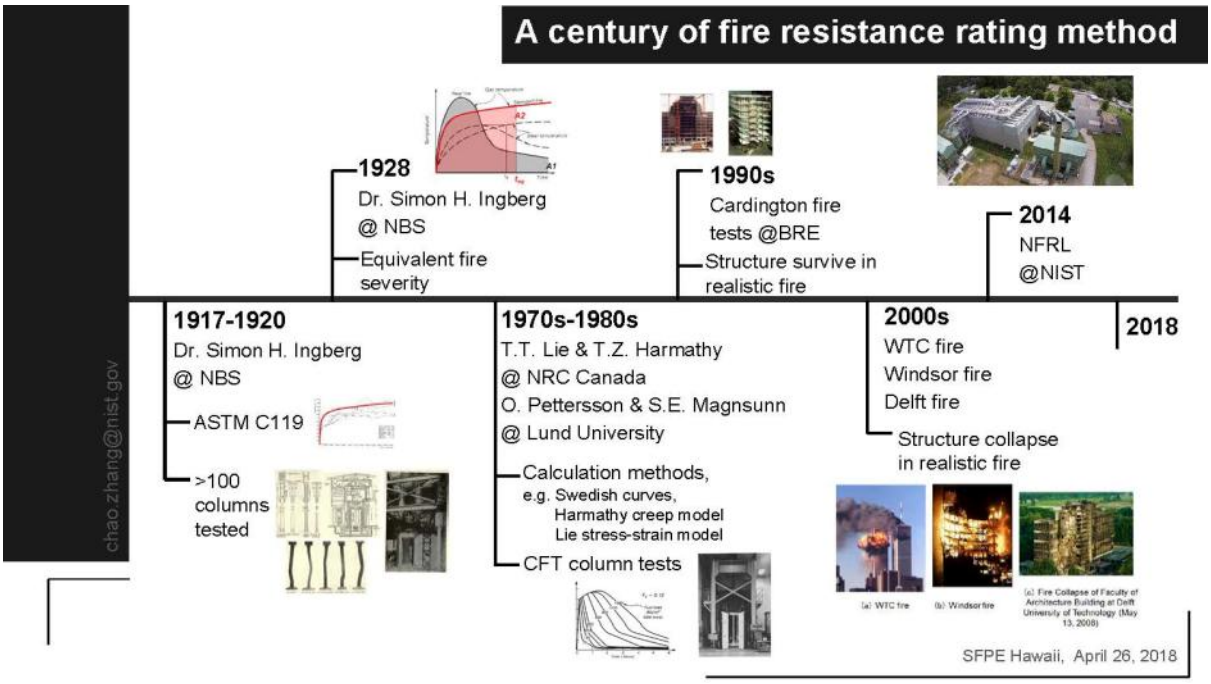

Safe or Not? It depends
Fire models
Failure behavior
Small room
$HRR = \dot{q}_g + \dot{q}_w + \dot{q}_{o,c} + \dot{q}_{o,r}$
Localized fire
$E(H) = \int_0^H E_z dz$
$E_z(dz) = (1-\alpha)F\epsilon\sigma \times (T_g + 273)^4$
(a)
(b)
Temp °C
Plastic strain
标准火 (582 °C)
整体失稳破坏
局域火1 (732 °C)
局部失稳破坏
(c)
Temp °C
Plastic strain
Location
(440 °C)
局域火2
12


FDS-FEM Approach
FDS-FEM
FDS model
AST, h_c
FE thermal model
T_s
FE structural model
Fire-structure interface
Load transfer method
Hasemi et al.'s test
Temperature
Displacement
(Bottom flange temperature)
(Mid span deflection)
NFRL Commissioning test


(a) Simple fire model
(b) Temperature distribution
Case study
Beijing new airport project
(a) Simple fire model
(b) Temperature distribution
(c) Plastic strain
Engineering design approach


(a) Simple fire model
(b) Temperature distribution
Case study
FDS predict AST
AST
P299×14
P457×24
P508×24
P600×25
time (min)
Temperature distribution from AST
Structural deformation at 90 min
Original analysis, column failure at 75 min


(a) Simple fire model
(b) Temperature distribution
FDS-FEM approach or FDS approach?
NFRL Composite beam test
(on going)
Complex geometry and 3D heat
conduction (under development)


A century of fire resistance rating method
1928
Dr. Simon H. Ingberg
@ NBS
Equivalent fire
severity
1990s
Cardington fire
tests @BRE
Structure survive in
realistic fire
2014
NFRL
@NIST
2018
1917-1920
Dr. Simon H. Ingberg
@ NBS
ASTM C119
>100
columns
tested
1970s-1980s
T.T. Lie & T.Z. Harmathy
@ NRC Canada
O. Pettersson & S.E. Magnsunn
@ Lund University
Calculation methods,
e.g. Swedish curves,
Harmathy creep model
Lie stress-strain model
CFT column tests
2000s
WTC fire
Windsor fire
Delft fire
Structure collapse
in realistic fire
chao.zhang@nist.gov
SFPE Hawaii, April 26, 2018

Unsolved problems to my understanding

chao.zhang@nist.gov

1. Scientificity of Fire resistance rating

Only for ensuring structural safety,
- ◆ What are the required FR ratings?
- ◆ Can structural members (e.g. beams, columns) have different required FR ratings in a same compartment?

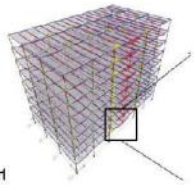
2. Large enclosure

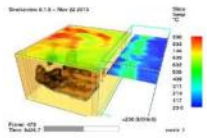
How safe is a PB design?

Chicago ORD airport

Open floor office

3. Validated, sophisticated numerical tool





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Thank you for your attention

Questions?

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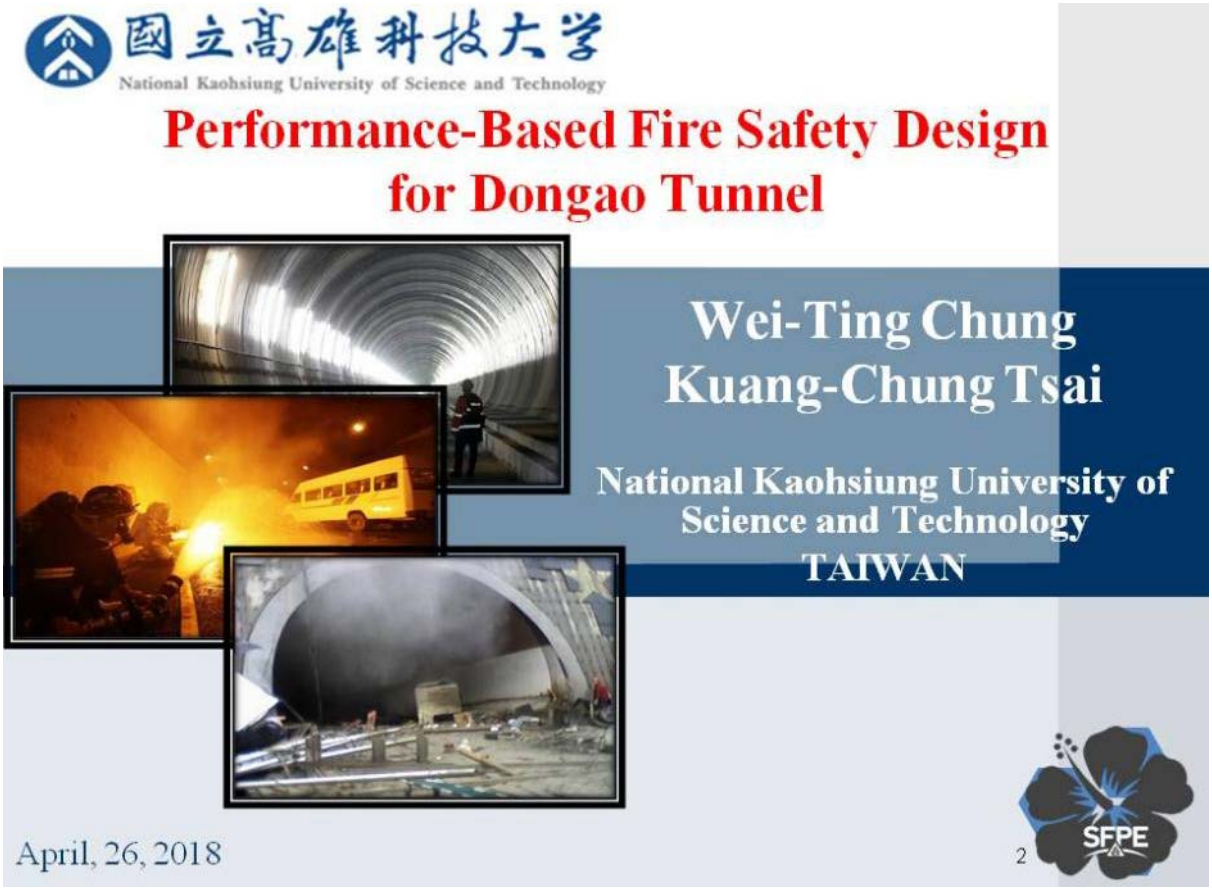
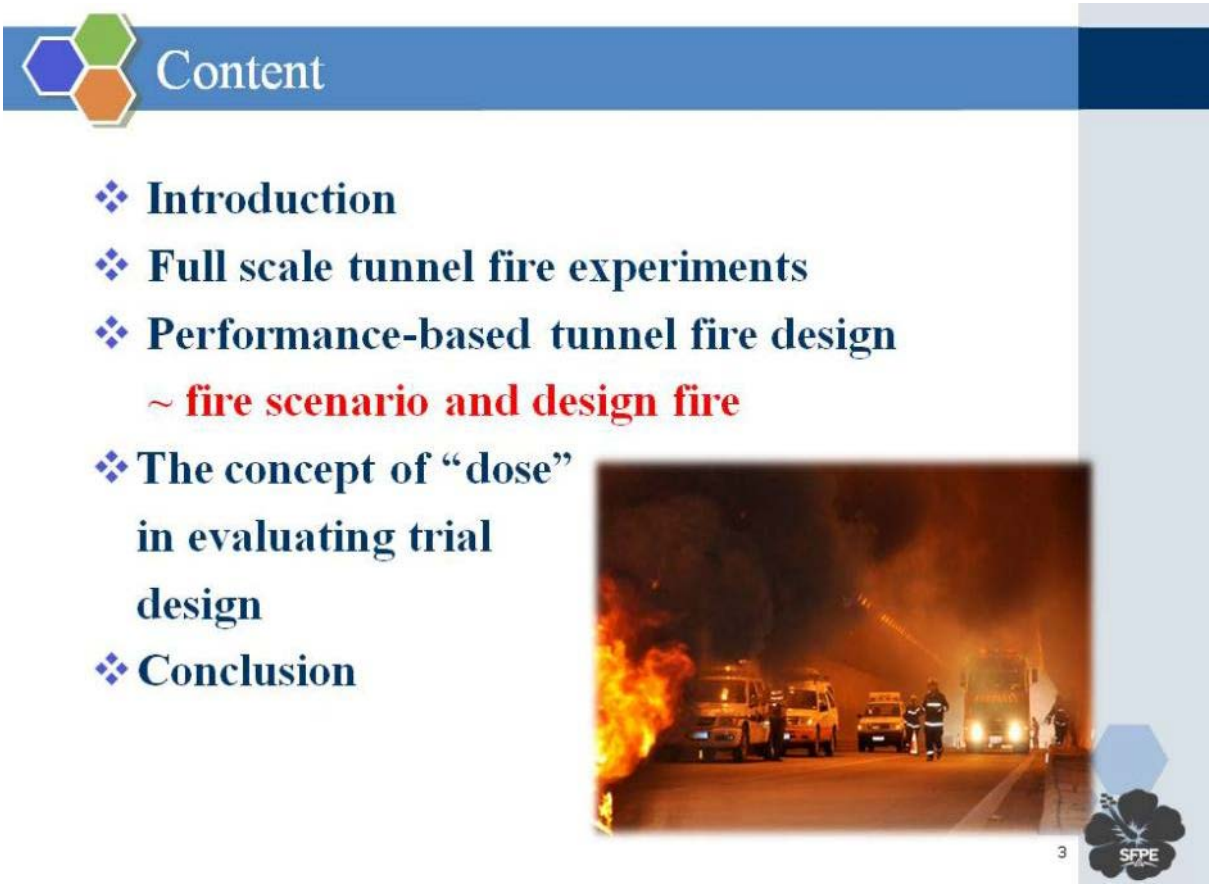
- 東澳隧道性能式防火設計





Introduction

- Many tunnels have been constructed to promote economic development in rural areas.
- Road tunnel fires are more dangerous than rail tunnels.

▼Baguashan tunnel (4.9km) ▼Pengshan tunnel (3.8km)

▲Hsuehshan Tunnel (12.9km) ▲Guanyinshan tunnel (2.5km)

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Introduction

- Road tunnel fires are dangerous due to its unique confined geometry, causing hot environment (temperature up to 1000℃).
- Road tunnels are sometimes built far from unban areas or in the mountains, so it is a challenge for fire brigade to rescue or suppress tunnel fires.
- When road tunnels are long, the risk increases.

Taiwan-Hsuehshan Tunnel

Switzerland-The Gotthard Tunnel

5

Introduction

❖ Incidents in road tunnels

Year	Tunnel	Length	Reason	Casualty loss	Others
1999	Mont Blanc tunnel	11.6 km	Butter in a truck caught fire.	39 dead, 23 HGVs, one small truck and 9 cars	Severe damage (900 m), the tunnel closed for 3 years
1999	Tauern tunnel	6.4 km	A truck crashed with four cars	12 dead, 49 injured, and 16 HGVs, 24 cars destoryed.	Closed for 3 months.
2001	St. Gotthard Tunnel	16.3 km	Collision	11 dead, 4 buses, 14 truck, 6 cars destroyed.	Severe damage for 230 m, closed for 2 months
2005	Frejus tunnel	12.9 km	Engine fire	2 dead, 21 injured and 4 HVGs destoryed.	10 km of equipment to be repaired.
2014	Yanhou tunnel, China	0.8 km	Two tankers	31 dead, 42 vehicles destroyed.	

Introduction

❖ The incident of Hsuehshan Tunnel in Taiwan in 2012

- Length: 12.9 km
- Cause of fire: A truck crashed into the back of a bus.
- Consequences: 2 dead and 31 injured

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New Su-Hua road tunnel project

- New tunnel project in Taiwan: Su-Hua road
- 8 tunnels with total length of 23.6 km. Dongao tunnel (3,380 m) is the first tunnel in Taiwan to install water mist system.

Suao and Dongao section

uni-directional tunnel
- Suao Tunnel (0.3km)
- Dongao Tunnel (3.4km)
- Dongao Tunnel (0.2km)

Nanao and Heping section

uni-directional tunnel
- Wuta Tunnel (0.5km)
- Guanyin Tunnel (7.9km)
- Gufeng Tunnel (4.7km)

Hechuang and Dachingshui section

uni-directional tunnel
- Chung-jen Tunnel (3.8km)

bi-directional tunnel
- Jen-shui Tunnel (2.9km)

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New Su-Hua road tunnel project

- In prevent tunnel fire incidents and to reduce the cost, Taiwanese government decided to install water mist system rather than to station a fire brigade. This water mist system can suppress tunnel fires, allowing the neighboring fire brigade to arrive and response shortly.

- This presentation introduces the experimental results, the process and challenges when performance-based design is conducted.

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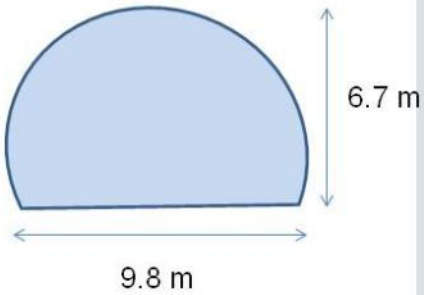
Full scale tunnel fire experiment

- The length of the tunnel is 88 m.

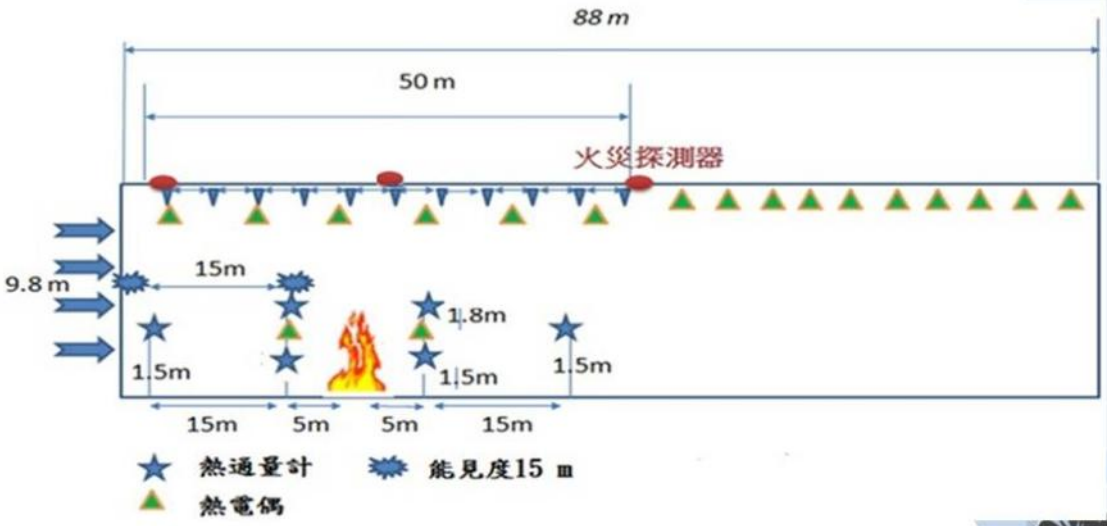


cross-section geometry of the tunnel

10

Experimental set-ups: Ventilation fan

- Measurements: heat flux, temperature and visibility.
- The parameters correspond to performance criteria.



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Safety Performance Criteria

Assessment Category		Parameter	The safety criteria
Life safety of tunnel users (Evacuation Environment) at height of 1.8 m.		Temperature	60℃
		CO concentration	800 ppm
		Visibility	10m
		Radiant Heat Flux	2kW/m^2
Life safety of fire fighters (Firefighting Environment) at positions of 20 m from fire and 1.5 m high.		Radiant Heat Flux	5kW/m^2
Structure explosion (Spalling of concrete)	0.8 cm inside the ceiling concrete	Temperature	380℃
	5 cm below the ceiling concrete	Temperature	500℃
Fire spread in Traffic Jam at positions of 5 m upstream and downstream from fire and 1.5 m high.		Radiant Heat Flux	12.5kW/m^2

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Experimental set-ups

Sprinkler head

Flame detector

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Experimental set-ups

piping

valve

Control panel

Water mist operation

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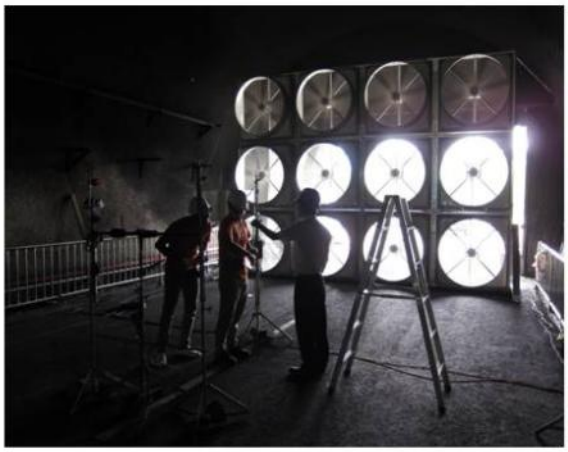
Experimental set-ups: Ventilation fan

A full cross-sectional fan system was used to simulate the effect of jet fans at 250 m far from fire source.

Wind speed: 1.5、2.5 m/s.



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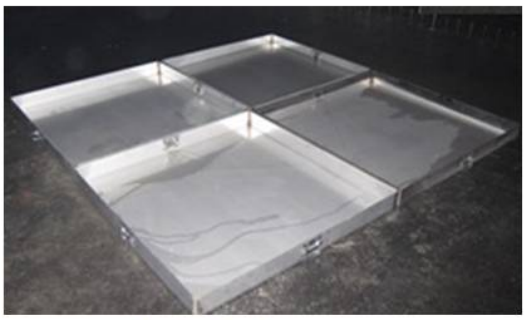
Experimental set-ups: HRR of fire source

❖ **Fuel: gasoline**

$1m^2$ fuel pan: 2.5 MW



$4m^2$ fuel pan: 10 MW

$9m^2$ fuel pan: 25 MW

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Parameters

Fire size	Water mist system	Velocity
$1\ m^2$	NO	Free burning
		1.5 m/s
	YES	NO
		1.5 m/s
		2.5 m/s
$4\ m^2$	NO	Free burning
		1.5 m/s
	YES	NO
		1.5 m/s
		2.5 m/s
$9\ m^2$	NO	Free burning
	YES	NO
		2.5 m/s

Ventilation operated when fire started. Water mist system actuated three minutes after fire occurred.

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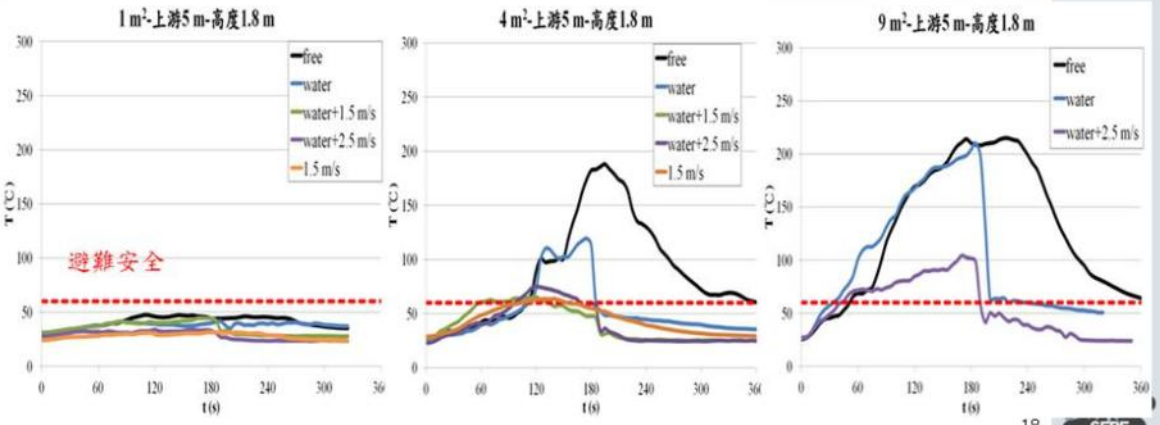
Experiments results

- **Life safety of tunnel evacuees (Evacuation Environment) at height of 1.8 m.**
- Free burning: >200℃ dangerous
- With ventilation: dramatic temperature drop
- With ventilation and water: dropped more



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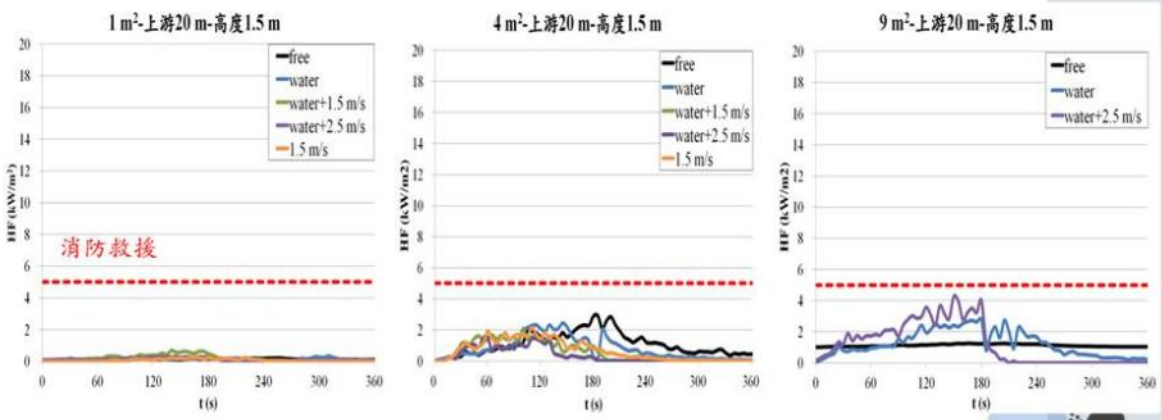
Experiments results

- **Life safety of fire fighters (Firefighting Environment) at positions of 20 m from fire with a height of 1.5 m.**
- Heat flux <5 kW/m² at 20 m from the fire.



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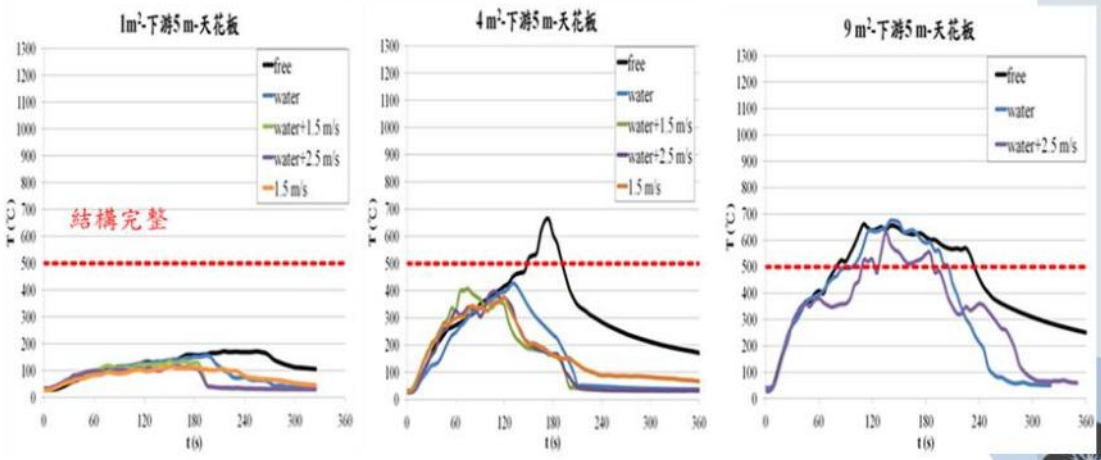
Experiments results

- **Structural damage (Spalling of concrete)**
- Ventilation strongly decreased the temperatures although the downstream ceiling temperature for large fires still exceeded the criteria value of 500℃.



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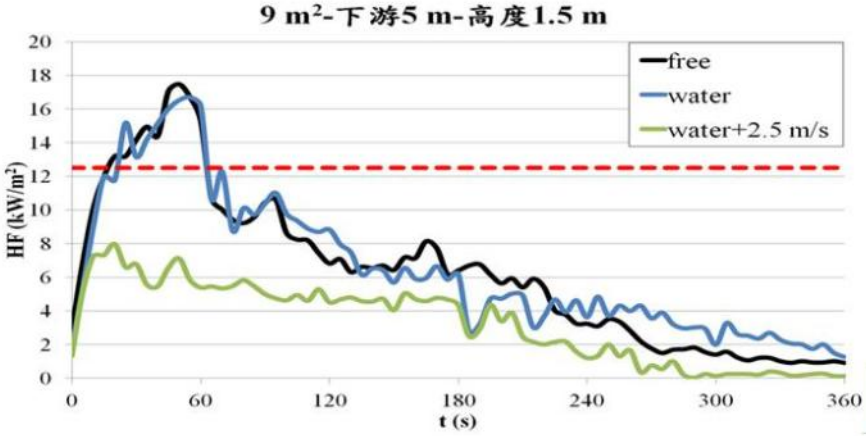
Experiments results

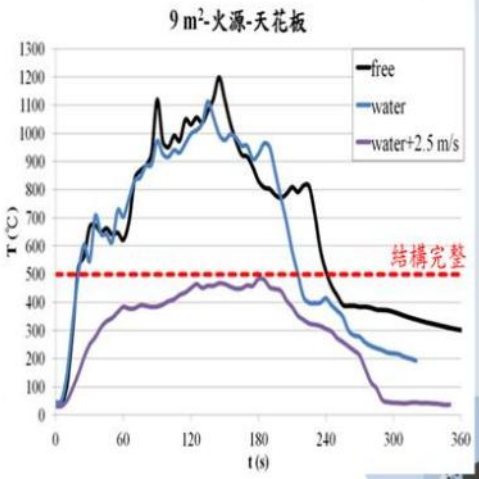
- **Fire spread at positions of 5 m upstream and downstream from fire with a height of 1.5 m.**
- Downstream flame spread may occur for free burning cases.
- Ventilation and water system reduced the downstream heat flux.



21

Discussion of full scale experiments

- The ventilation system can generally generate a safe environment for evacuees and fire fighters, and prevent flame spread through vehicles, except the position very close to fire source.
- The temperature of concrete exceeded 500℃ until water mist system actuated.
- Water mist system can extinguish a large fire, but not a small fire because sufficient vaporized water can generate. However, water mist cannot extinguish a fire, large or small, when ventilation system is on.



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Performance-based tunnel fire design

- New tunnel project in Taiwan: Su-Hua road
- 8 tunnels with total length of 23.6 km. Dongao tunnel (3,380 m) is the first tunnel in Taiwan to install water mist system.

Suao and Dongao section

uni-directional tunnel
- **Suao Tunnel (0.3km)**
- **Dongao Tunnel (3.4km)**
- **Dongao Tunnel (0.2km)**

Nanao and Heping section

uni-directional tunnel
- **Wuta Tunnel (0.5km)**
- **Guanyin Tunnel (7.9km)**
- **Gufeng Tunnel (4.7km)**

Hechuang and Dachingshui section

uni-directional tunnel
- **Chung-jen Tunnel (3.8km)**

bi-directional tunnel
- **Jen-shui Tunnel (2.9km)**

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Performance-based design for tunnel fires

❖ Performance-based design

- An engineering approach to fire protection design based on (1) agreed upon fire safety goal and objectives, (2) deterministic/ or probabilistic analysis of fire scenarios, and (3) quantitative assessment of design alternatives against the fire safety goals and objectives using accepted engineering tools, methodologies, and performance criteria.

(The SFPE Engineering Guide to Performance-Based Fire Protection)

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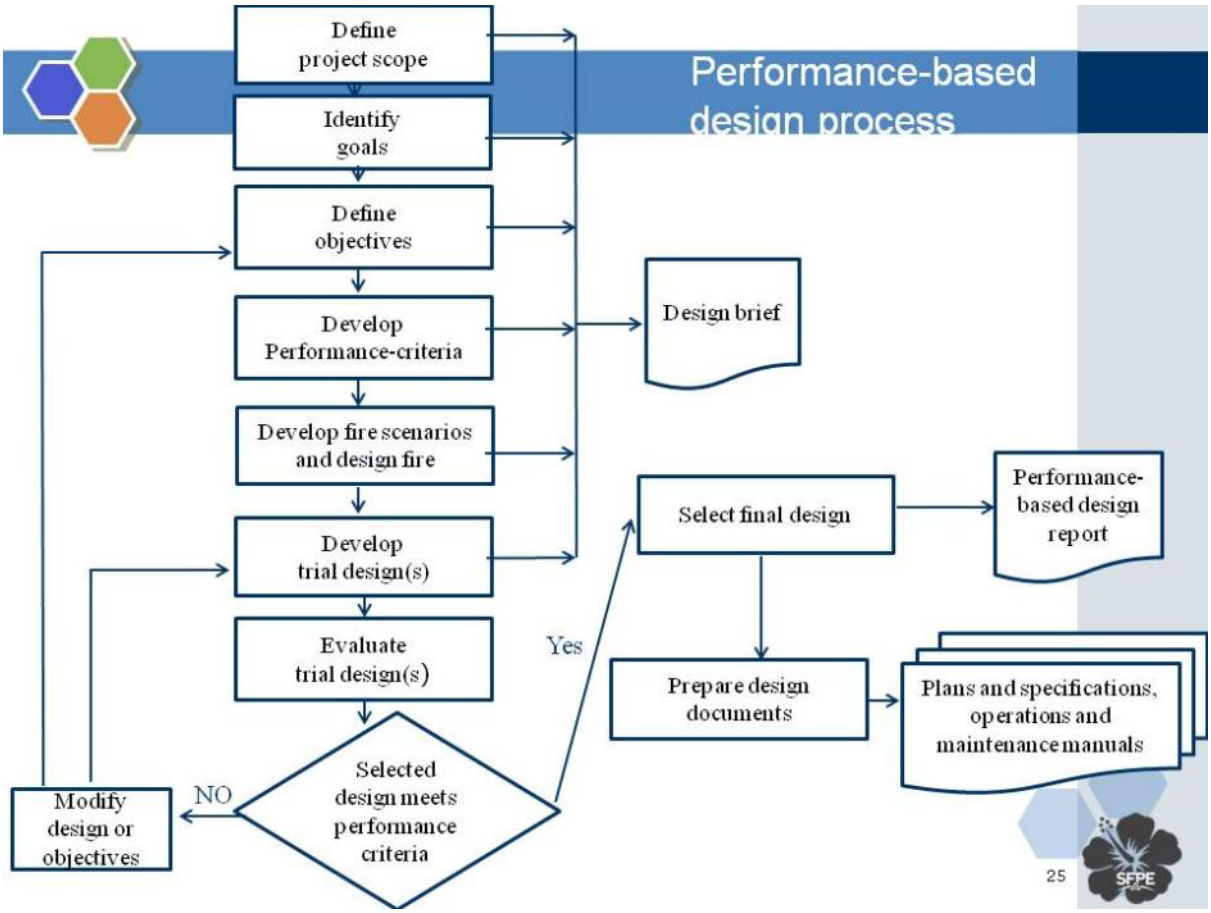
Performance-based design process



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Goal, Objectives and Performance Criteria

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Structure explosion (Spalling of concrete)	0.8 cm inside the ceiling concrete	Temperature	380℃
	5 cm below the ceiling concrete	Temperature	500℃
Fire spread in Traffic Jam at positions of 5 m upstream and downstream from fire and 1.5 m high.		Radiant Heat Flux	12.5kW/m^2

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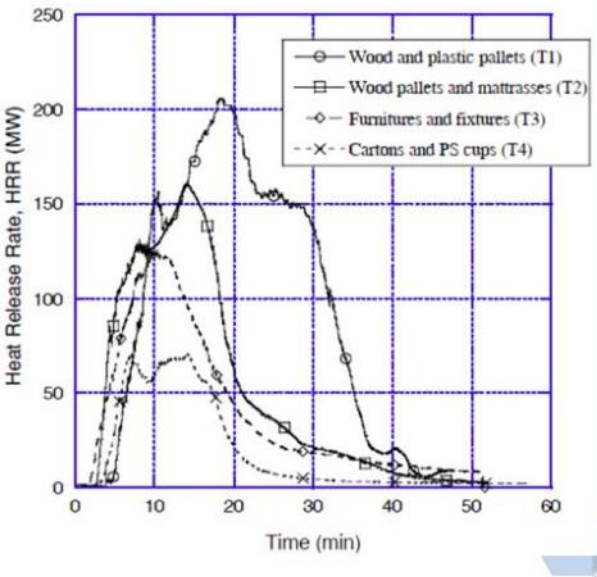
Performance-based tunnel fire design

- **Fire scenarios and design fires** → **worst case**

- **Fire scenario A**
  - A truck incident resulting in 100 MW fire



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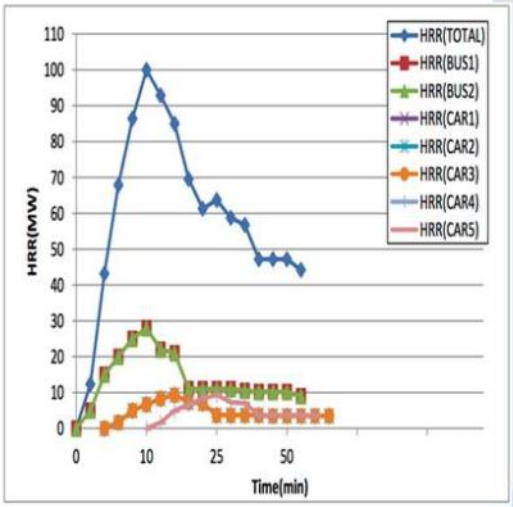
Performance-based tunnel fire design

- **Fire scenarios and design fires → worst case**

- **Fire scenario B**
  - Two buses accident and involving 5 cars
  - 100 MW fire



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Performance-based tunnel fire design

- **Fire scenarios and design fire → worst case**
- Fire location
  - Smoke control system
  - The slope effect
  - Piston effect
  - External wind
  - Relative positions of smoke vents, water mist region and evacuation tunnel
  - Traffic jam

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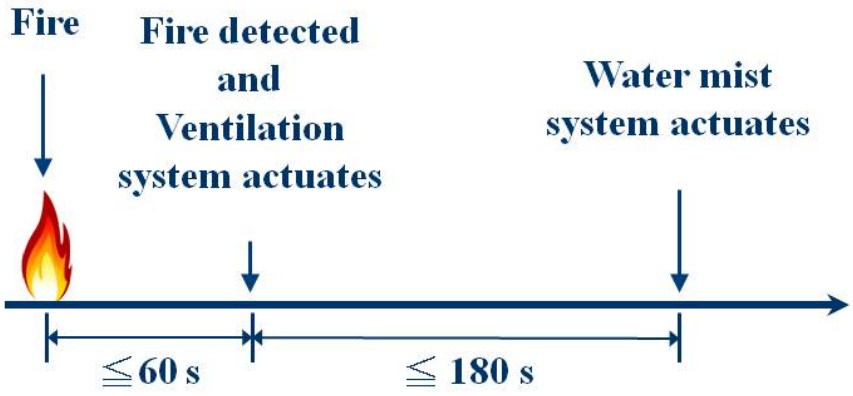
Performance-based tunnel fire design

❖ **Timeline of fire fighting facility actuation**

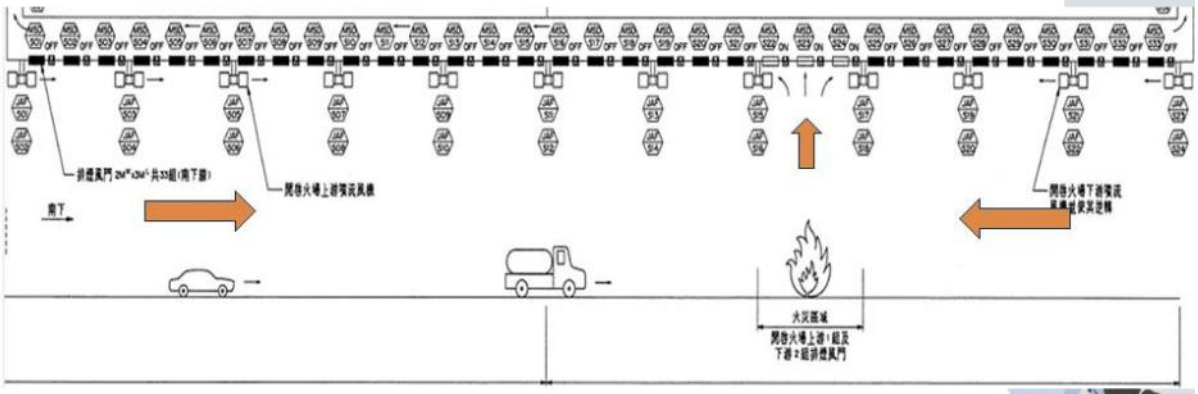


30

Performance-based tunnel fire design

❖ **The tunnel ventilation system in Dongao Tunnel includes**

1. Jet fans near two tunnel portals to push smoke towards smoke vents, and prevent smoke flow outwards
2. Smoke exhaust system draws smoke through three 2×3 m^2 vents



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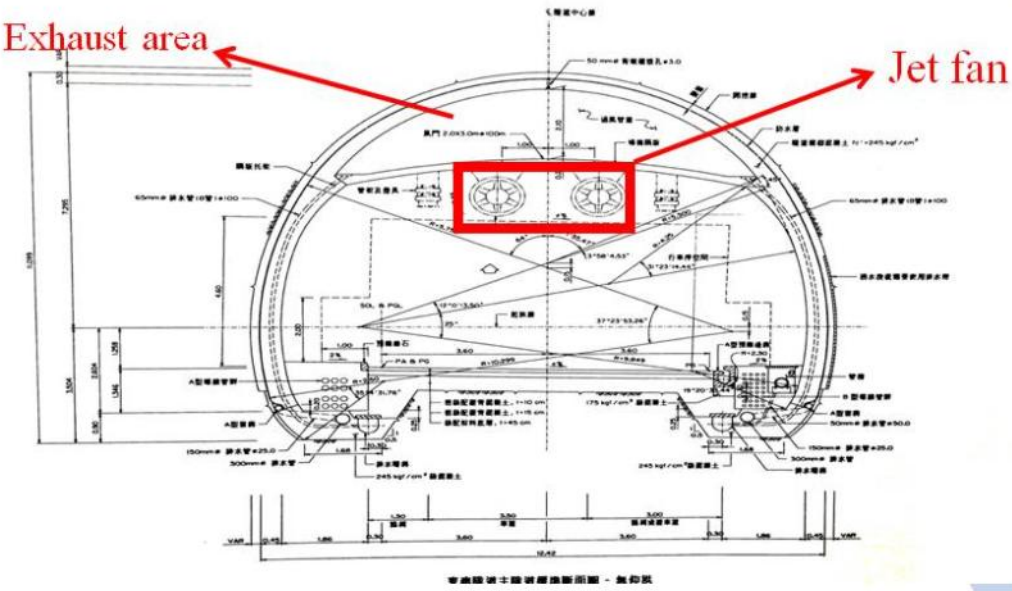
Performance-based tunnel fire design

- Dongao tunnel



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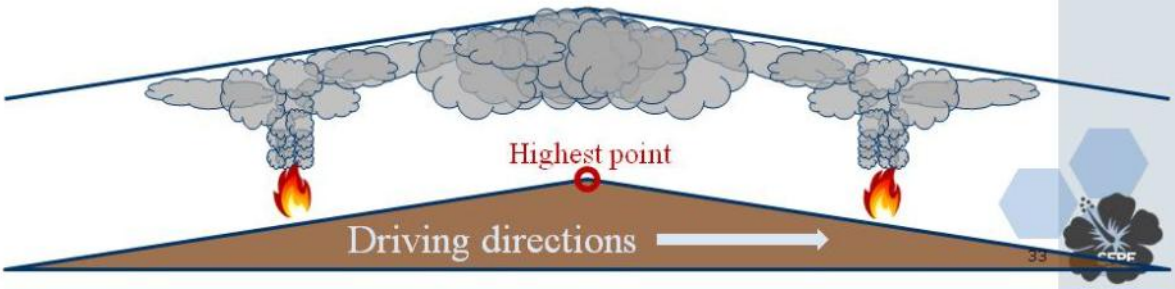
Performance-based tunnel fire design

- **The slope of the tunnel**
  - A fire occurs upstream from a higher point of a tunnel
    - The smoke accumulates toward the downstream direction. If this direction is the same as the direction of jet fan, the smoke flow accelerates.
  - A fire occurs downstream from a higher point of the tunnel
    - The smoke accumulates toward the upstream direction. Turbulence is generated due to its opposites direction to the jet fan. The smoke layer remains near the high point.



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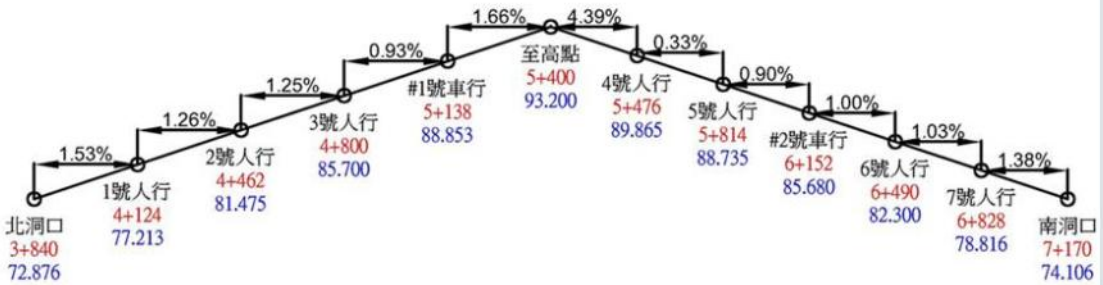
Performance-based tunnel fire design

❖ The slope of Dongao tunnel

- The highest location is at the center.
- The effect of gradient differs with the fire location in the tunnel.



東澳隧道(南下線) 縱斷圖 高程示意圖

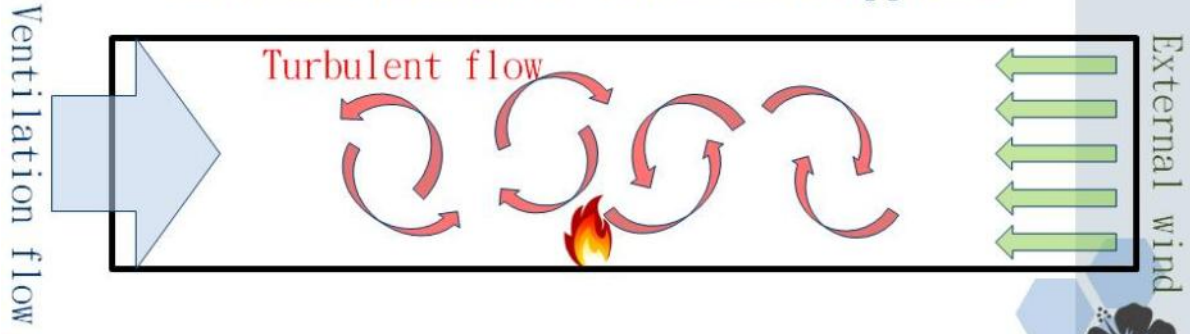
Performance-based design for tunnel fires

❖ Piston effect

- **Piston effect comes from the flow formed by moving vehicles.**
- **Direction: downstream**
- **Piston effect depends on**
  - Vehicle speeds:
    Higher vehicle speed induces higher flow speed inside the tunnel.
  - Vehicle size:
    Piston effect caused by large vehicles is higher than those for small vehicles due to the larger blockage of the tunnel by the large vehicles.
  - Vehicle spacing:
    The piston effect is increased when the vehicle spacing decreases.

Performance-based design for tunnel fires

- **External wind near the tunnel portal**
  - The external wind changes the flow near the tunnel portal.
  - If the directions of external wind and ventilation are consistent, the effect of ventilation is enhanced. If not consistent, the effect of ventilation is suppressed.



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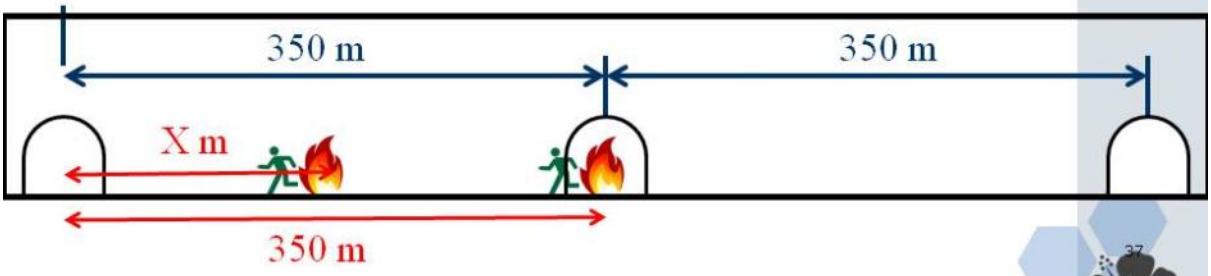
Performance-based tunnel fire design

- **Position of evacuation tunnels**
  - The distance between two evacuation tunnels is 350 m.
  - Fire occurs between two evacuation tunnels
    - Evacuee needs to walk for X m.
  - Fire occurred near an evacuation tunnel
    - Evacuee needs to walk for 350 m.



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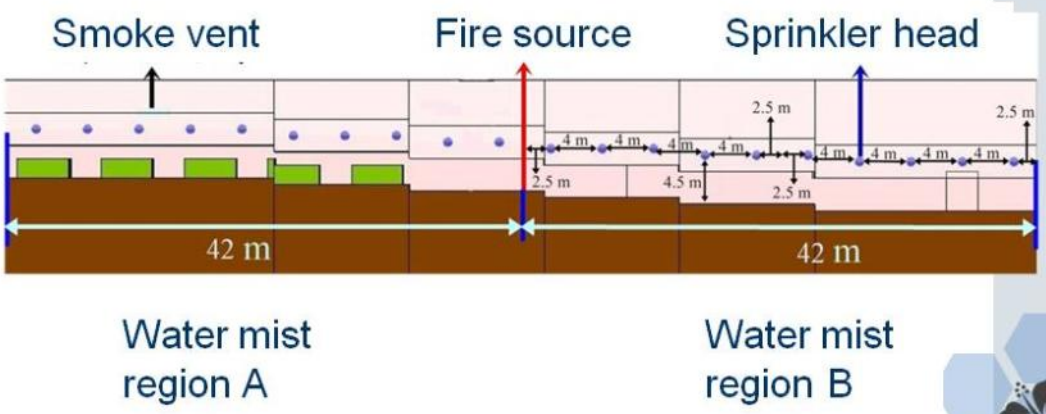
Performance-based tunnel fire design

❖ Position of water mist region

- The distance of one water mist region is approximately 50 m.
- Two regions will be operated in a fire



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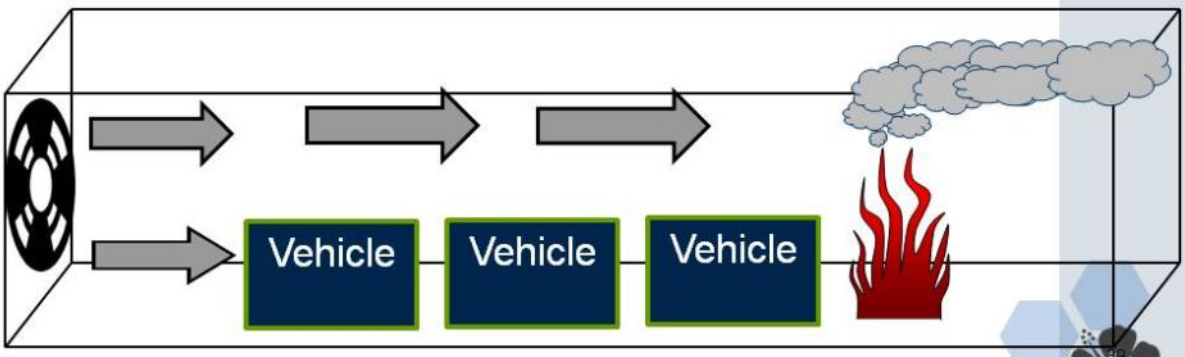
Performance-based design for tunnel fires

❖ Traffic jam in the tunnel

- Any incident in a tunnel makes vehicles upstream queue behind the incident location. The ventilation flow is blocked by the vehicles.
- The vehicles downstream move to the tunnel portal.



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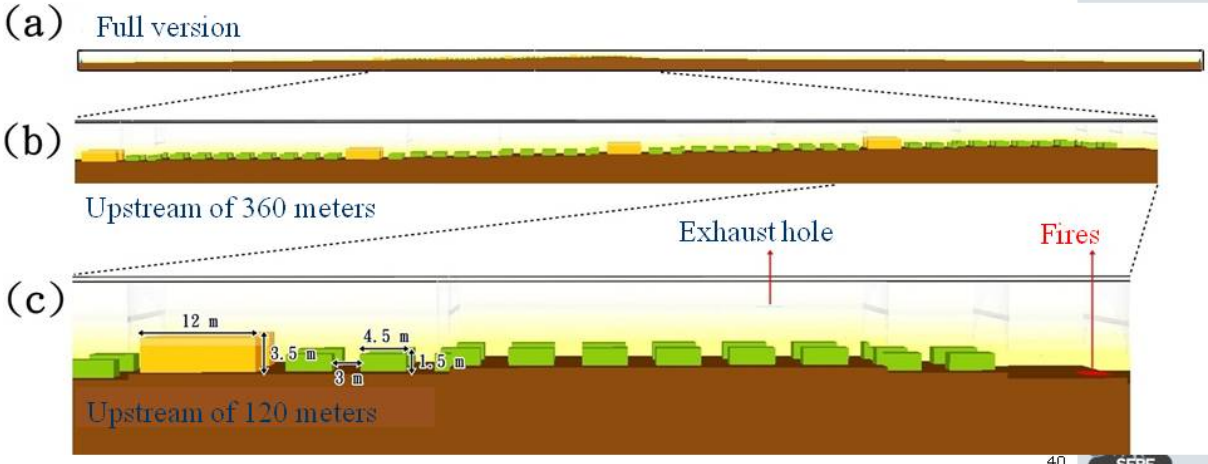
Performance-based tunnel fire design

- Traffic jam effect
- The ratio of all kinds of vehicles is from a governmental survey, given 1:10 (bus: car).
- The traffic jam effect is more dangerous when a fire occurs near the downstream portal. A long queueing line is formed.



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Performance-based tunnel fire design

- Which fire location may lead to the "worst" case
- Risk assessment is necessary.

Smoke control system	The flow behavior is complicated in the central section
The slope effect	Strong near the central section
Piston effect	Strong near the central section
External wind	Strong near tunnel portal
Positions of smoke vents, water mist operation region and evacuation tunnel	The relative positions need to be considered
Traffic jam	Strong near the downstream portal

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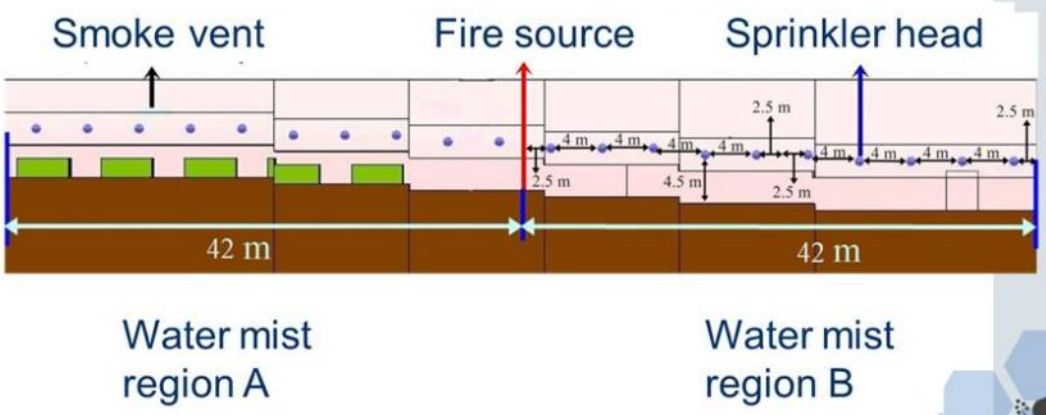
Performance-based design for tunnel fires

- Trial design: a fire occurs at a position 34 m downstream the highest point.
- Evaluating the trial design by FDS to see whether this trial design can satisfy all the performance criteria.



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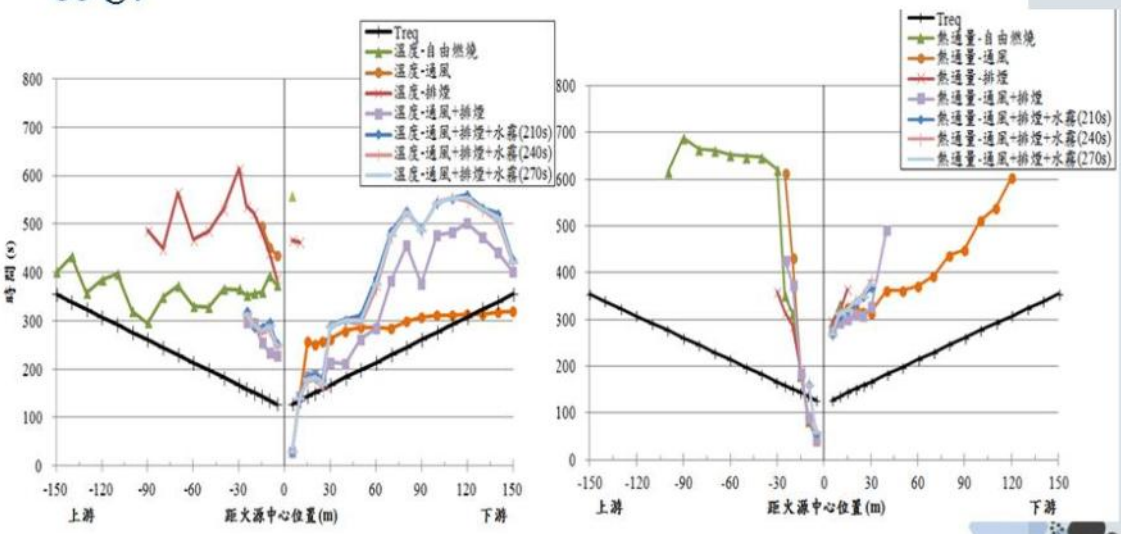
Evaluation of the trail design

- **Simulation results:**
- **The temperature within 5 m from the fire source still exceeded 60℃.**



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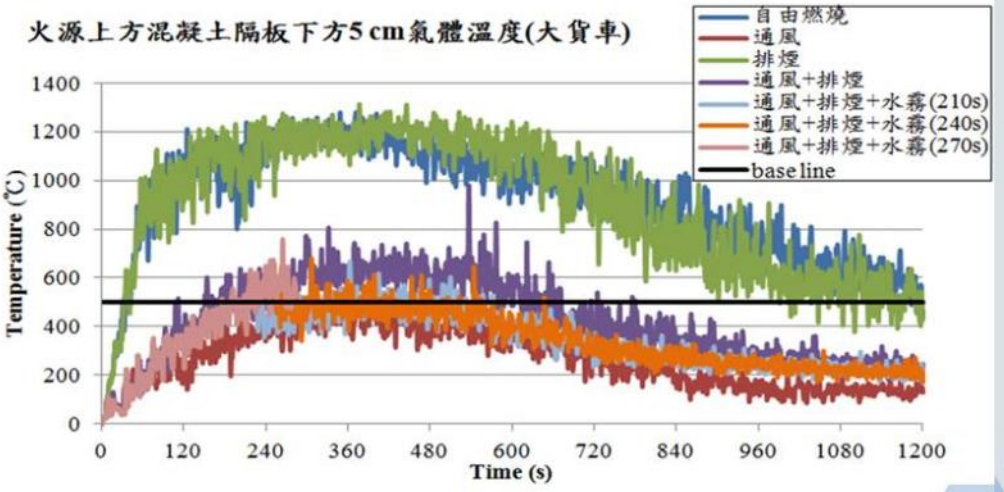
Evaluation of the trail design

Simulation results:

The temperature above the fire source exceeded 500℃.



Evaluation of the trail design

The concept of "dose"

Life safety criteria address the survivability of people exposed to fire or fire products. The values selected as performance criteria might vary depending on the physical and mental conditions of building occupants and length of exposure. (The SFPE Engineering Guide to Performance-Based Fire Protection)

Performance criteria may need to be developed in the area of thermal effect to people, (e.g. exposure to high gas temperature or thermal radiation), toxicity of fire products, or visibility through smoke.

Evaluation of the trail design

- **The dose of radiative heat flux**

Mode of Heat Transfer	Intensity	Tolerance Time
Radiation	<2.5 kW/m^2	>5 min
	2.5 kW/m^2	30 s
	10 kW/m^2	4 s

- **Arioz investigated the effects of elevated temperatures (from 200 to 1200 ℃ for 2 hours) on properties of concrete.**
- **The concrete started to crack when the temperature increased to 600 ℃ but the effect was not significant at that temperature level.**

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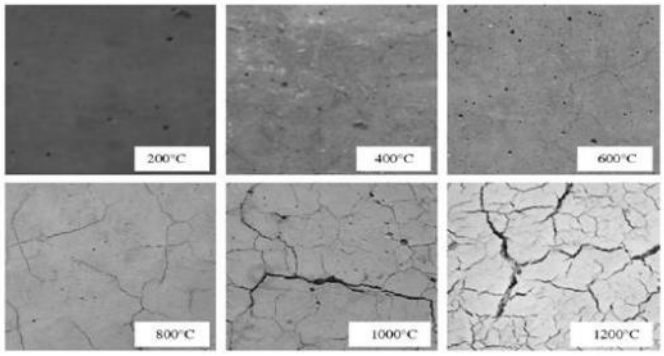
Evaluation of the trail design



- **The cracks became very pronounced at 800 ℃ and extensively increased at 1000 ℃.**
- **The specimens completely decomposed and lost their binding properties after exposure to 1200 ℃ where the spalling of the samples due to excessive cracking was observed.**

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Conclusions

- A full-scale tunnel fire experiment was conducted in Taiwan to better understand experimentally the integrated effect and individual effect of water mist and longitudinal ventilation on tunnel fire. The experimental results show that the ventilation plays an important role in the emergency response action in tunnel fire. Water mist can help suppress the fire and protect the concrete.
- The fire safety design of Dongao tunnel was conducted according to the process of performance-based design.
- The worst case is always needed when considering "fire scenarios and design fires". Two fire scenarios were applied, a truck fire and a fire involving two buses and five cars.

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- When set up the location of fire, the pattern of smoke control system, the slope of tunnel, piston effect, effect of external wind, relative positions of smoke vents, water mist region and evacuation tunnel, and traffic jam effect should be considered. These effects may have different impact on fire and evacuation. (One may be against another!)
- The concept of "dose" is needed when evaluating whether the trial designs can satisfy all the performance criteria.

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Current situation

- 10 MW test conducted to confirm the operation of all fire fighting facilities on December 20, 2017.
- Dongao Tunnel opened on Feb. 5, 2018!

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Thank you
For Your Attention

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