出國報告（出國類別：考察）

第 9 屆結構火災安全國際會議及建築防火實驗技術交流考察

服務機關：內政部建築研究所
姓名職稱：鄭元良 主任秘書
陳柏端 約聘助理研究員
派赴國家：美國
出國期間：中華民國 105 年 6 月 4 日至 6 月 12 日
報告日期：中華民國 105 年 9 月 7 日

摘要

為了解國際上結構火災及建築防火實驗技術發展趨勢，本所派員赴美普林斯頓大學參訪，並參加第 9 屆結構火災安全國際研討會。本次行程主要是拜會普林斯頓大學土木與環境工程學系 Garlock 教授，就其研究領域之複合性災害、實驗研究、數值分析等方面，交換雙方研究心得，並談到在工程專業教育上，如何傳達設計理念與方向，用心規劃課程為學生創造學習環境，並參觀普林斯頓大學圖書館學生作品展示，了解學生學習成果。

在研討會方面，主要是蒐集國際上防火實驗技術及結構火害最新研究資料，包括(1)在不同溫度下材料基本性質研究，如混凝土、鋼、木材及防火被覆材料等、(2)大型結構實驗屋火害試驗，如複合鋼梁火害結構行為和樓版薄膜效應研究、及(3)數值分析方法及使用軟體。這些研究資料及經驗，對本所今年進行實尺寸鋼構屋火害實驗，及規劃後續研究與發展計畫，皆有相當之助益。

目錄

一、目的

(一)前言

為了解美國及國際間最新動態，作為本所未來規劃建築防火與鋼構建築複合性災害耐火科技發展計畫，及擬訂研究課題之參考，於今(105)年 6 月 4-12 日至美國普林斯頓大學，進行國際結構火災及建築防火實驗技術交流考察，並參加第 9 屆結構火災安全國際研討會(Structures in Fire, SiF)。其中除拜會普林斯頓大學土木與環境工程系 M. Garlock 教授，討論國際結構防火趨勢及發展外，並蒐集相關建築結構耐火研究及防火實驗技術資料，作為本所研究計畫及我國建築結構耐火規範之研訂參考。

(二)效益評估

本計畫效益如下：

1 藉由參訪了解美國及國際間最新動態，作為本所未來擬訂研究課題，及規劃建築防火與鋼構建築複合性災害耐火科技發展計畫之參考。

2 促進我國在建築防火科技研究之國際交流，並蒐集相關建築結構耐火性、多重災害對建築結構損害評估，以及災後社會復原能力評估等研究，作為我國建築結構耐火規範之研訂及防災規劃參考，對於提升建築防火安全等公共安全議題均有莫大助益。

(三)參訪人員

本次參訪人員為本所鄭元良主任秘書及陳柏端約聘助理研究員 2 人。

(四)參訪行程

本次參訪行程為拜會普林斯頓大學土木與環境工程系 M. Garlock 教授，參觀 Friend Center Library，及參加第 9 屆結構火災安全國際研討會，行程如下：

1. 拜會普林斯頓大學土木與環境工程系 M. Garlock 教授
   時間：6 月 6 日(一)上午 10 點整
   地點：Eng. Quad E 307, Dept. of Civil & Environment Engineering

2. 參觀 Friend Center Library
   時間：6 月 6 日(一)下午
   地點：Friend Center and Computer Science Building

3. 參加第 9 屆結構火災安全國際研討會
時間：6 月 7 日至 6 月 10 日
地點：McDonnell Hall
研討會議程：詳見附錄一

二、過程

(一)拜會普林斯頓大學土木與環境工程系 M. Garlock 教授

Garlock 教授研究領域是在複合型災害方面，包括災害後社會復元能力、建築結構耐火性能設計、建築物震後火災調查研究、鋼構造橋梁火害研究、鋼構件接頭火害行為研究，除了數值分析外，也積極與各大學及研究單位合作進行大型結構火害實驗，其研究領域非常廣泛，研究成果也常於國際重要期刊上發表。

本屆結構火災安全國際研討會於普林斯頓大學舉辦，由該校土木與環境工程系承辦，Garlock 教授負責擔任主辦人。雖然工作非常忙碌，她還是非常樂意接受本所拜會。本次與 Garlock 教授見面地點就在她的研究室內，如圖 1 所示，討論內容包括複合性災害、地震後火害、鋼構件接頭火害、與結構耐火性能設計相關研究。討論議題與內容簡述如下：

圖 1 與 Garlock 教授在研究室內進行討論

議題一：複合性災害研究-火災與地震

本所於台南防火實驗室新建實尺寸鋼構實驗屋，預計於今(105)年完成，原規劃進行火害後地震研究，但有學者建議台灣多 RC 建築，不似日本以木構造建築為主，地震後較易發生火災。所以今年先進行火害前與火害後動態結構行為量測，再進行載重下火害實驗，以了解我國常用的剪力連結型式複合鋼梁，受到真實火害的結構反應與行為。

對於建築物複合性災害研究，Garlock 教授認為，大尺寸實驗規劃進行非常不容易，尤其是與火害相關研究，更是稀少，所以對於本所能在這方面規劃長期相關實驗計畫，給予極高的肯定與支持。在過去火災與地震複合性災害研究方面，一般來說是以地震後火災研究為主，因為從歷史資料來看，如 1995 年在日本發生的阪神地震，震後火災所造成的建築物損失及人員傷亡，是相當嚴重的。不過對本所即將進行的火害前後結構動態行為量測，Garlock 教授也相當有興趣，她認為可從不同角度進行火害對於主結構之影響，這些資料也可以供地震研究者在實驗前對建築物耐震能力進行折減，是屬於相當寶貴的資料。

Garlock 教授也提供日本 Jun-ichi Suzuki 博士進行火害快速評估研究資料，日本目前約有 41-75 萬棟木構造建築，且在全日本建築中，約有 4.5-7.5 萬棟是防火建築，已經不是如過去一樣以木構造建築為主，在大地震來襲後容易引起火災發生。雖然震後火災研究仍需進行，但目前在建築結構複合性災害研究方面，國際上認為非結構材的破壞也很重要，因為非結構材損壞除了會影響後續營運功能外，火與煙也容易流竄到其他房間，造成人員的傷亡。

Garlock 教授舉出美國加州聖地牙哥 Englekrik 實驗研究中心，自 2009 年進行 3 年 5 層樓實尺寸震後火災實驗計畫(這也是本所台南防火實驗室規劃鋼構實驗屋所參考的資料之一，如圖 2 所示)，全面性探討非結構材與系統受火害與地震的反應，如屋頂供水及空調系統、灑水管線及電路系統、天花板開口、逃生通道及電梯、基礎隔震系統等，受到地震衝擊損傷後的建築防火安全性能，及災後能繼續營運所需之設計與考量因素。

雖然聖地牙哥 Englekrik 實驗中心計畫與本所鋼構實驗屋實驗目標不同，但是在實驗規劃方面，還是有非常多實驗細節值得本所參考，如載重塊設置、火載量大小、通氣口尺寸等實驗條件、實驗量測與觀測位置，及最後實驗屋破壞模式，有助於本所規劃階段性實驗，並能順利完成。

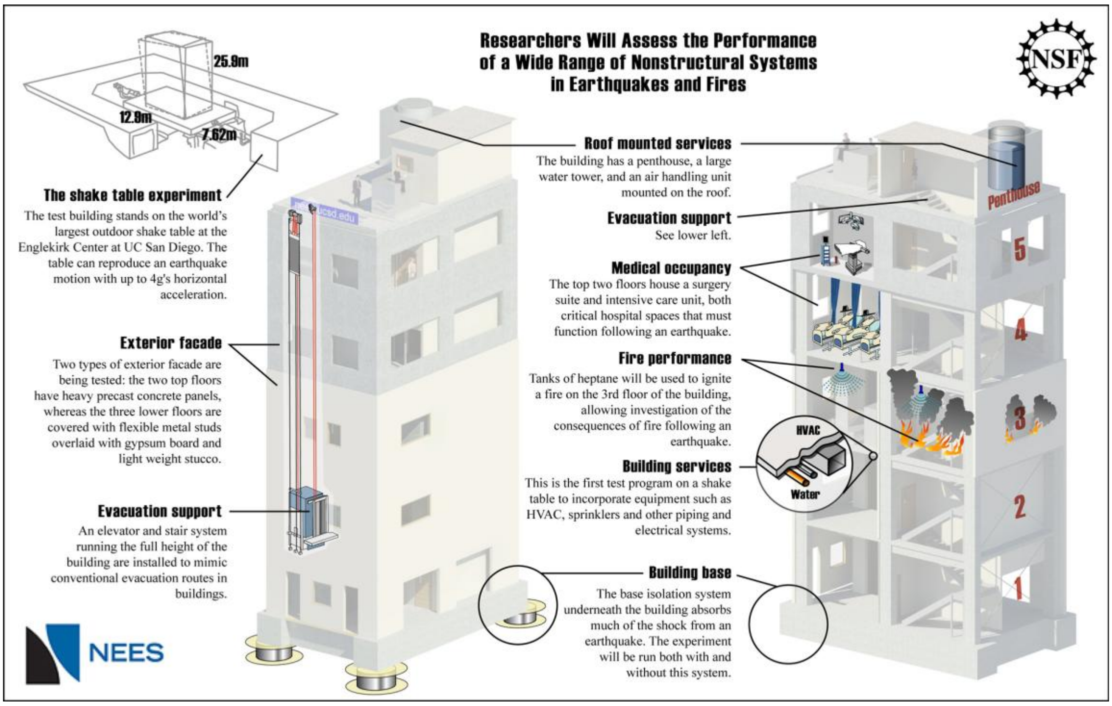


圖 2 美國聖地牙哥 Englekrik 實驗研究中心實尺寸複合性災害實驗計畫

議題二：實驗研究-剪力接頭

在鋼構造建築樓版下方小梁兩端是以剪力接頭栓接於大梁，受到高溫火害破壞時，將造成樓版塌陷，依照我國現行建築法規，梁之防火時效須達 1 小時，包括與大梁相連接的小梁。為了達到法規要求，一般在工程上都使用防火被覆，但民間業者為節省經費，希望能免除小梁之規定，理由為小梁因上有樓版蓋覆，且兩端接頭處溫度不會如梁中央高，因此建議小梁可以不用做防火被覆。

為了探究梁接頭的破壞模式，本所於 104 年完成「抗彎矩構架之梁構件火害研究」，探討柱束制大小對於梁之破壞影響，並於今(105)年進行「含剪力接頭鋼構造梁之耐火性能研究」，及「實尺寸鋼構屋之剪力連接複合鋼梁火害結構行為研究」，探討簡支梁承受重力荷重於火害下之結構行為，然而囿於經費因素，無法進行足夠數量的試驗，而且受限於量測儀器，對於許多重要數據，如梁軸力變化、挫屈時間、塑性鉸位置等，無法設置適當之量測儀器得到資料。

Garlock 教授表示，剪力接頭的破壞模式對於鋼構架是非常重要研究，她是取英國 Cardington 鋼構架火害實驗模型(如圖 3 所示)，完成數值分析方法，並與實驗數據做比較，探討梁接頭(包括螺栓)的破壞模式。

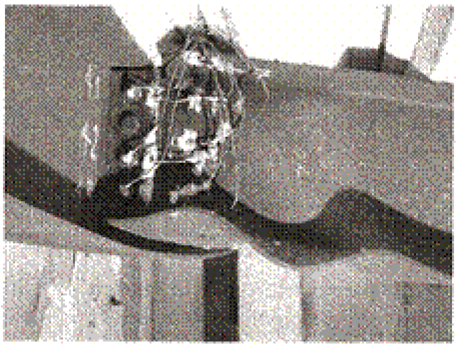


圖 3 Cardington 鋼構架火害實驗-梁接頭破壞模式

對於本所相關研究，Garlock 教授提供一些建議供參考，一般剪力接頭破壞模式為腹板先挫屈，接著是下翼板，如圖 4 所示，最後是螺栓破壞，如圖 5 所示，破壞模式的判斷準則於目前仍未定，最粗略的是以結構是否倒塌為主。有關螺栓破壞模式，在她的研究結果中顯示，螺栓孔邊距只要大於 1.5 倍孔徑即可，過大效果增加不多，且在高溫時螺栓大多為剪力破壞控制，只是如何提高這部分強度則是另一研究課題。另外，Garlock 教授提出她目前思考的研究方向供本所參考，即如何讓剪力接頭強些，她認為可朝提高延展性，而不是增加材料強度來試，也應可增加防火時效。

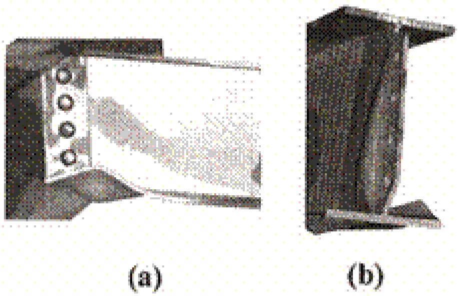


圖 4 鋼梁剪力接頭破壞模式(a)腹板先挫屈，(b)下翼板挫屈

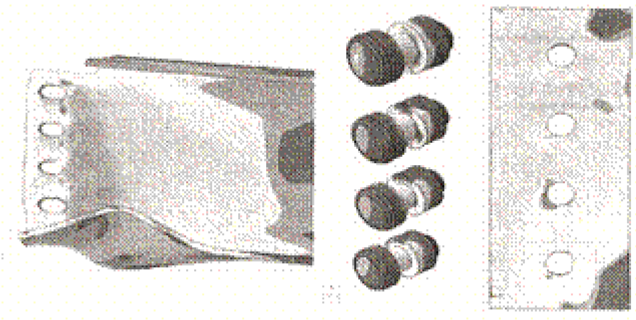


圖 5 鋼梁剪力接頭螺栓破壞

對於本所研究梁接頭使用單加勁板，Garlock 教授建議多注意實驗時冷卻階段，在此階段會產生大的軸向拉力，對於梁的承載力是重大考驗，容易因不穩定，造成樓版崩塌。

議題三：數值分析

進行大尺寸結構火害實驗不容易，所需經費也多，若能佐以數值分析，除了可與實驗數據比較，更可進行參數分析，得到較多的資料供參考。不過在一般數值方法所用的是 standard method，而 Garlock 教授曾於文獻中提及選用 explicit method，這種分析方式比較少人使用，故請教其選用之理由。

Garlock 教授表示，在數值分析中，這兩種方式各有優劣，當初在選擇時，就有很大的掙扎。大多數使用者會選擇 standard method，因為比較直接，程式在每一步驟運算結束後，會檢查力學平衡是否在容許範圍內，若超過容許值時，程式會重新運算，直到滿足容許條件，使用者不用費心去注意。只不過若是模型過大，例如結構火害這類實驗，不容易收斂，造成程式計算的時間會很久。

而選擇使用 explicit method，程式進行中不會檢查運算結果是否仍維持力學平衡，所以需要使用者提供適當的控制，如使用元素大小、穩定的時間增量、適當的數值內插方式、動力效果控制、以及接觸雜訊等，這些都需要有良好的力學基礎與使用程式的經驗，否則對於所獲得結果的正確性，會有很大的疑慮。

議題四：教育

在一般大學土木相關系所基本課程中，多是鋼結構設計、混凝土結構設計、及預力混凝土設計等，比較少有專門為防火設計開設課程，普林斯頓大學在課程方面，如何給予學生結構防火基本訓練。

Garlock 教授表示，普林斯頓大學規模比較小，全校約有 5000 位學生，以土木與環工系來說，大學部每年只招收 15 至 20 位學生，研究生更少，只有 5 至 10 位。雖然學生人數少，但因素質好，學校允許大學部學生選修研究所的課程，另外還有實際操作課程，也很有幫助，亦即與外校老師合作，尤其是有關實驗方面如與密西根州立大學、理海大學等共同開課。普林斯頓大學土木與環工系本來有自己的力學實驗室，不過因為缺乏有經驗的老師管理而在她進入前關閉，無法讓我們參觀。

在結構防火基本訓練方面，因系上教授力學的老師不多，只有 2 位，加上系上規定必修課程多，實在無法為了結構防火單獨開一門課程，所以只能在她教授的鋼結構課程中，儘可能加入 1 至 2 周的結構防火課程，以概念性設計為主，讓學生先有觀念，至於深入研究，則可讓學生以專題研究的方式，或是進入研究所後再行加強。

議題五：建築結構耐火性能設計

結構火害行為複雜，從各種材料性質、單一構件行為、或是整體構架行為，存在許多變數與不確定因素，變數可以用實驗或數值分析入手，但不確定因素就需要從大量資料中慢慢分析。一般是從機率及可靠度分析入手，雖然可將許多難以從實驗獲得的因素納入考量，但是這種方法一方面過於數學，不易理解，另一方面過於抽象，難以想像。目前來說，在材料方面的問題較易解決，但在結構火害行為方面因實驗少且複雜，仍無既定評估公式可遵循，還需要很長的時間才能獲得較為具體的成果。

Garlock 教授表示，自 911 世貿大樓恐怖攻擊發生後，各國政府曾投入大量經費從事結構火害相關研究，然而時至今日，火害研究熱潮已漸漸冷卻下來，卻還有相當多的基礎研究沒有完成，例如在建築材料的鋼、混凝土、木材等與溫度變化之基本力學性質(彈性模數、極限強度、降伏強度)，熱性質(比熱、膨脹係數、熱傳導)，都還不清楚，且結構火害的破壞行為方面仍須進行諸多實驗印證，這些都是造成結構火害行為仍難以預測，且與數值分析結果仍有相當大的落差的原因。

應用機率概念的性能設計法是一個可以努力的方向，雖然還需要各研究單位共同努力增加實驗資料，不過，能從有限資料中，運用機率方法，對許多不確定因素，歸納出關鍵性的影響因子，並給予適當的權重，讓設計者能從諸多參數中理出頭緒，且有信心進行設計。性能設計法除了可用來量化材料及結構火害的不確定因素外，還可用來進行可靠度評估，在已知火害情境下評估結構安全。

由於性能設計法內容離真正的規範訂定仍有距離，目前是先在設計規範(AISC 360)附錄 4.1 結構火害設計中放入一小段概念性敘述，如圖 6 示，等未來內容逐漸增多及成熟後，再納入規範中。

Performance-based design: An engineering approach to structural design that is based on agreed-upon performance goals and objectives, engineering analysis and quantitative assessment of alternatives against those design goals and objectives using accepted engineering tools, methodologies and performance criteria.

圖 6　AISC 360 規範附錄 4.1 結構火害性能設計概念敘述

(二)參觀 Friend Center Library

Friend Center Library 隸屬於普林斯頓大學工程教育圖書館，提供工程相關雜誌、論文、圖書、電子書、線上百科及教室供師生使用，一樓大廳則是展示區，展出學生學期中的作品，如圖 7 所示。

這是土木與環境工程系高年級課程 CEE463: A Social and Multi-Dimensional Exploration of Structures 學生作品，本課程每 2 年一次，每次規劃不同主題，目的是將工程作品以藝術形式展現，學期結束後再將成果開放給社會大眾參觀。目前展出的作品是西班牙橋梁設計之藝術，是 2014 年秋季所開的課程，由 Maria M. Garlock 教授與西班牙 Valenica 大學 Ignacio Paya-Zaforteza 教授共同指導。

圖 7 Friend Center Library

課程規劃是在學期中，由 Garlock 教授與 Paya-Zaforteza 教授 2 位老師帶領著學生到西班牙中部及西南現場參觀一個禮拜，行程如圖 8 所示，主要是看完成於 1990 年代以後的現代橋梁，並研究所使用不同材料與建築系統。學生透過現場實地觀察，並直接與工程師及計畫執行者進行討論，以學習橋梁施工技術，和了解橋梁在地方上的作用與象徵意義。

圖 8 西班牙橋梁參觀行程

學期結束前，學生必須根據課堂中所學習橋梁設計概念，再將現場地形及觀察蒐集之資料，製做成模型作品。這對於學生是很大的挑戰，老師不會動手幫學生製作模型，學生們必須自組合作團隊，根據資料從地形、結構、材料等進行討論，思考如何動手，並繳交最後成品，如圖 9 所示。

Garlock 教授表示，這門課程是希望能結合文化創意、工程師的熱情、及追求完美細節等目標，並教導學生環境與施工過程融合的重要性，達到優美、效率、與經濟三者之結構藝術。所以在課程設計時，涵蓋大型建築與橋梁之規劃、設計與施工階段，讓學生從多方探討工程、藝術與社會之融合，並以最少的材料，展現建築的優雅與經濟。

優秀大學是課程與實際並重，除了學習工程外，還融入社會環境影響及經濟衝擊，並透過現場參觀及與工程人員對話，讓學生克服心理上及觀念上的問題，理想與實務能得到印證。這是一門非常不一樣的課程，讓枯燥的工程設計與美學、環境教育及社會關懷結合，訓練出具有專業與通才的學生。Garlock 教授表示，她除了授課壓力外，還得煩惱找經費支付所有旅費及模型花費，但最後看到學生們的學習過程與成果，覺得這一切努力都是值得的。

圖 9 學生作品 Almonte River Viaduct, Alcantara 水庫, 位於西班牙 Caceres

(三) 參加結構防火國際研討會

結構防火國際研討會(Structures in Fire, SIF)每 2 年輪流於歐洲、亞洲與美洲召開，主要目的是提供結構防火相關學術單位、研究機構及工程師們一個共同分享平台。

本次研討會有來自 26 個國家的專家學者參加，共有 150 篇文章發表，包括 135 篇以簡報形式，15 篇以海報形式呈現，探討主題包括混凝土結構(纖維混凝土，混凝土材料性質)、鋼結構(梁柱接頭、合成梁、鋼材料性質)、木構造、橋梁與非建築結構、實驗方法、防火安全機率分析、數值方法、及防火材料等，研討會報到、會場簡報及海報如圖 10-圖 12 所示，詳細議程如附件一。

圖 10 結構防火國際研討會報到

圖 11 結構防火國際研討會-簡報會場

圖 12 結構防火國際研討會-海報展覽區

本次研討會重點內容綜合簡述如下，共分為不同溫度下材料基本性質研究、大型結構實驗屋火害試驗，及數值分析軟體三大類，相關可供本所參考之文章摘要可參考附錄二：

1、不同溫度下材料基本性質研究：

國際上在結構火害方面的研究，仍缺乏不同溫度下鋼與混凝土之基本性質資料，如應力應變關係、潛變與高強度材料性質，這些基本資料對於結構火害實驗非常重要。目前國際結構防火設計規範如 AISC 360 及 EuroCode 3 是以列表方式，顯示重要轉折點資料(EuroCode 還加上公式與圖)，如材料彈性模數、降伏應力應變與極限應力應變等，仍缺少不同溫度下材料性質資料，另外，規範所列數值也偏保守，對於實驗研究及數值分析來說雖然可直接引用，但大多數研究者只能拿來作為參考。

混凝土及鋼材料在高溫時由於材料強度下降，性質開始變得非常敏感也不穩定，已非單純結構行為，而是進入到微觀的材料科學領域，故須探討如鋼材料化學組成，混凝土配比及骨材粒徑，環境影響，內部濕度及實驗時溫度升高速率等。另外高強度材料也開始被應用於建築、橋梁、隧道等工程，雖然可減少結構斷面尺寸，不過這些材料耐火性質不佳，以至於在高溫時對結構系統安全影響甚大，

目前這方面研究仍不足，需持續進行。有關混凝土爆裂行為較複雜，與其內部水分及纖維含量、溫度變化、軸向應力都有關，不過爆裂行為對於高強度材料如高性能混凝土及超高性能混凝土尤為重要，因與結構整體安全有關。

本次研討會材料方面文章很多，歸納為混凝土材料、鋼材料、木材料、及防火被覆材料 4 大類，內容簡述於下：

1.1 混凝土材料方面包括普通混凝土、高性能纖維混凝土、高強度混凝土及超高強度混凝土性能研究，摘要部分可參考附錄二-1。

(1) M. Neuenschwander 以實驗驗證混凝土受火害破壞塑性模式，以循環載重方式，控制應變速率調整軸向壓力，研究應力應變關係與塑性硬化區，實驗設置及試體於 500℃、600℃及 700℃破壞情形如圖 13 所示。

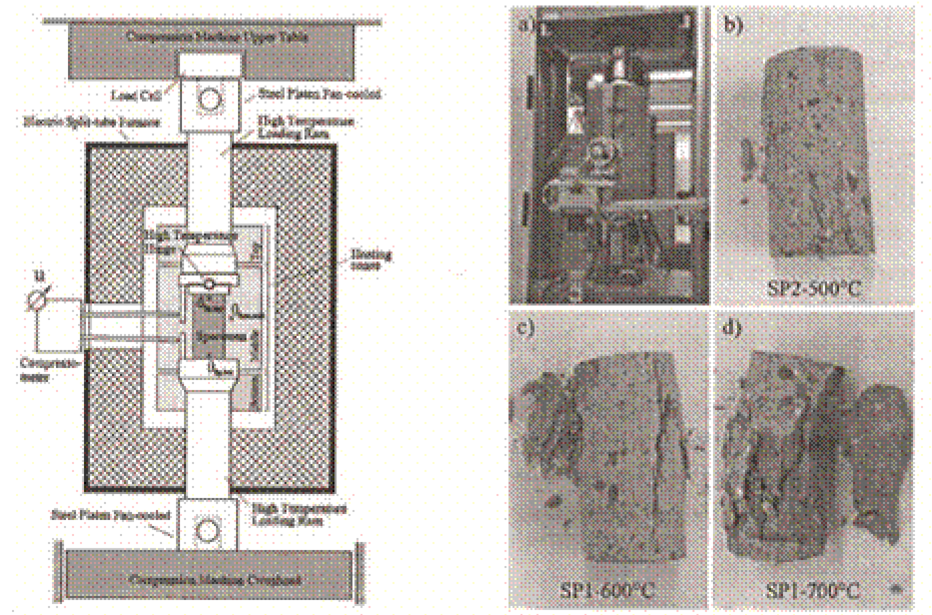


圖 13 實驗設置及試體於各溫度破壞情形

高溫壓力循環載重試驗可以檢測出混凝土彈性係數於塑性區受溫度變化減弱的行為，用來校正數值分析中混凝土於高溫中塑性破壞模型資料，圖 14 顯示彈性係數受高溫降低情形，其中(a)為彈性係數於波峰前與波峰後之差易，波峰前彈性係數維持穩定，但是超過波峰後，彈性係數下降快速，此性質與常溫時彈性係數幾乎不變差異相當大，(b)表示彈性係數與強度在波峰後折減之相關性分析，(c)至(e)表示運用此塑性破壞模型資料於數值軟體後，數值分析資料與實驗資料之比較。由圖可知，此模型可以提高數值分析之準確性，對於材料在高溫之行為具有極高參考價值。

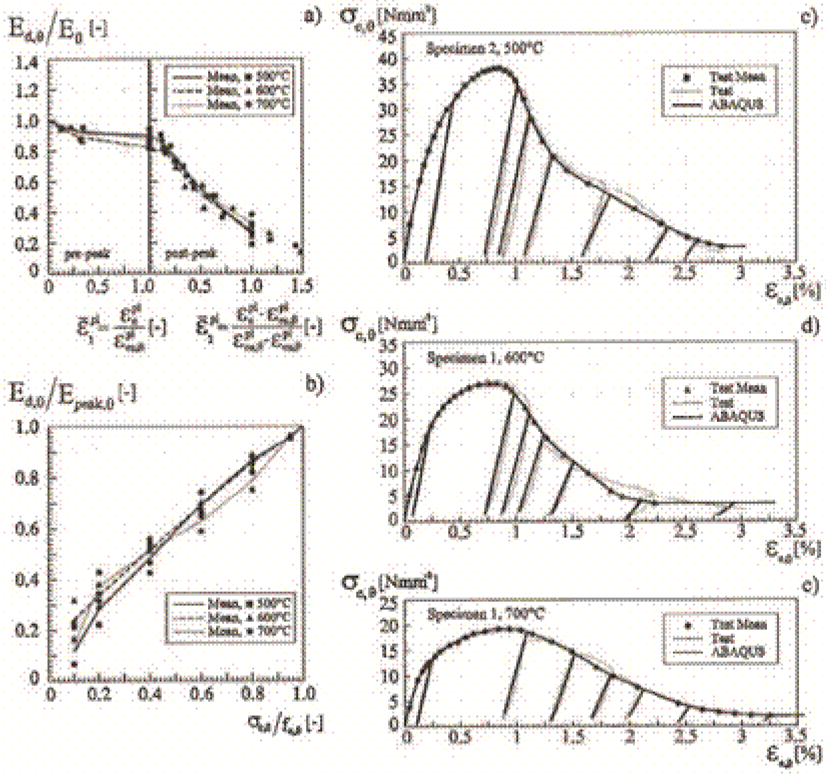


圖 14 混凝土彈性係數受高溫降低情形

(2) M. J. Miah 以雙軸向加壓實驗探討 2 種不同混凝土材料爆裂性質，發現即使混凝土受很小壓力，如 0.5 Mpa，對於混凝土爆裂行為也有影響，圖 15 顯示不同混凝土受軸向壓力破壞情形，B40-II 與 B40-III 兩種混凝土 28 天抗壓強度為 40 MPa，但壓力在 0.5 Mpa 時邊緣已開始出現裂縫，5 Mpa 至 10 Mpa 則完全破壞。

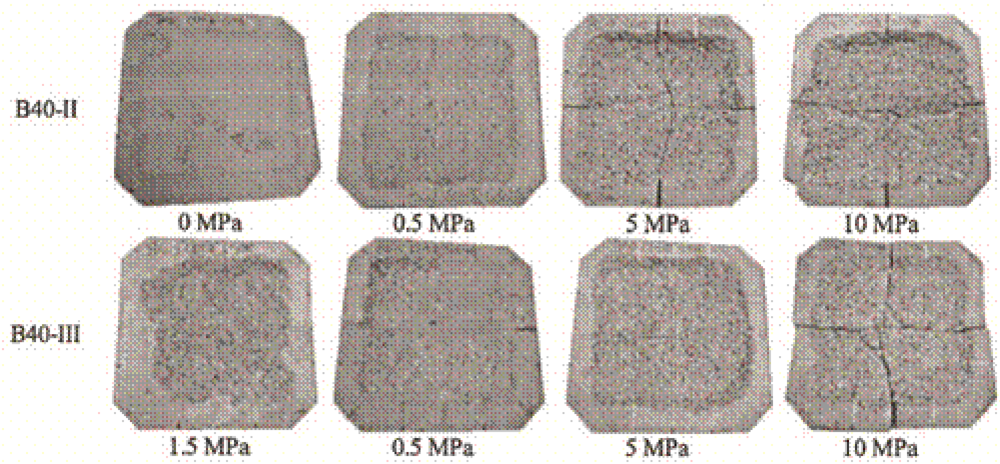


圖 15 不同混凝土受雙軸向壓力破壞情形

圖 16 顯示混凝土試體受雙軸壓力之變形曲線，壓力增加會縮短破壞時間，且位移有減少的趨勢。

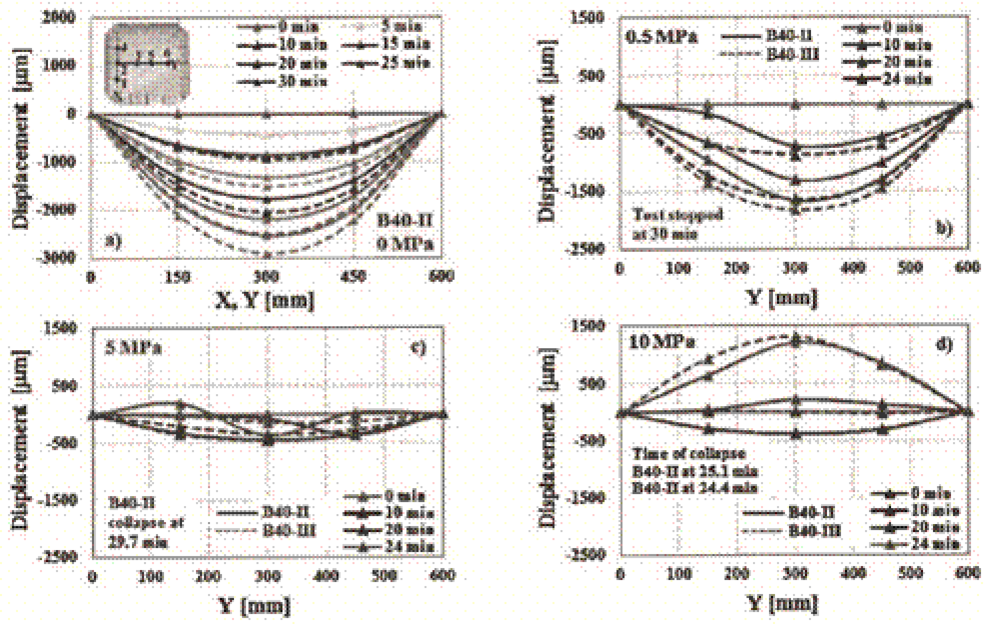


圖 16 混凝土試體受雙軸壓力變形曲線

(3) X. Li 探討高溫下高性能纖維混凝土性質，以不同含水量、含砂量、含纖維量、含飛灰量及高效塑化劑含量，研究在 200℃、400℃、600℃與 800℃之熱傳導性質，結果如圖 17 所示。

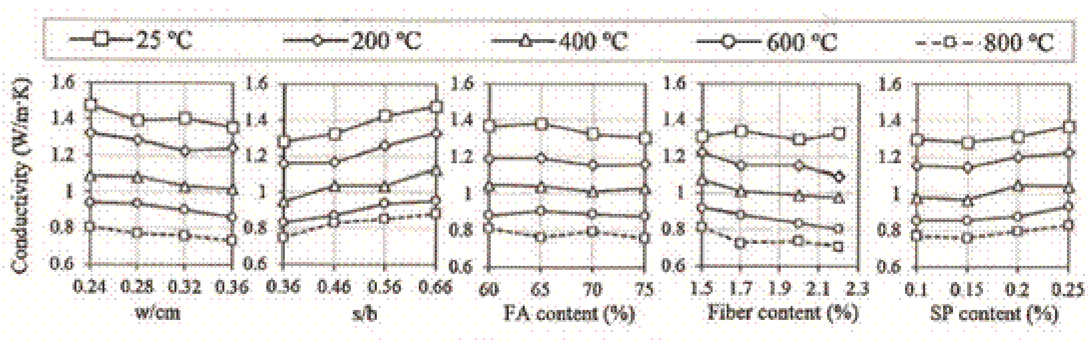


圖 17 混凝土在不同溫度不同配比之熱傳導性質

(4) M. Xiong 以實驗研究超高強度混凝土高溫性質，結果顯示，加 0.1%聚丙烯纖維有助於防止高溫(至 800℃)混凝土爆裂情形，另外，超高強度混凝土強度折減實驗結果與其他文獻比較結果如圖 18 所示，其中在 100℃時強度有突然下降，但是在 100℃-300℃會有回升情形，與其他文獻結果差不多。

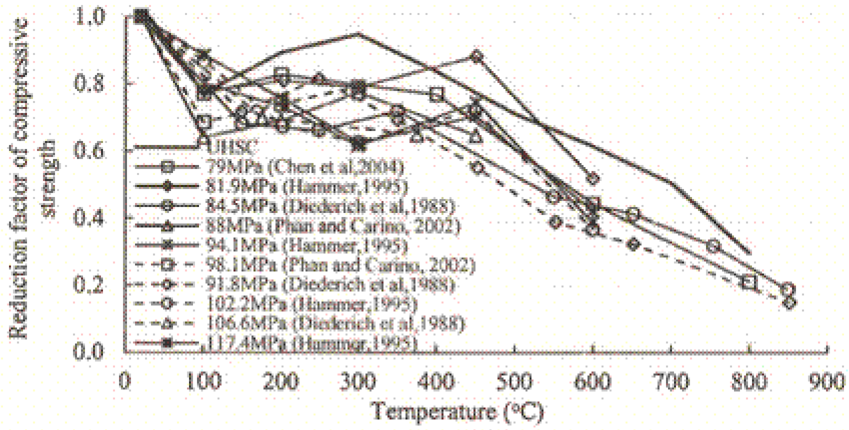


圖 18 超高強度混凝土強度折減實驗結果與文獻比較

(5) Marcela B. S. Sollero 探討使用火成岩粒料之高強度混凝土火害後殘餘性質，圖 19 顯示高強度與超高強度混凝土在高溫下殘餘壓力強度折減係數，可知混凝土所用粒料，無論是粗細或材料不同，對於強度都有影響，但是目前在 Eurocode 規範上並無任何考量這方面之因素，鑑於高強度混凝土使用越來越多，因此這些結果都是值得參考的資料，並在未來能增加溫度實驗範圍及各種不同粒料的使用。

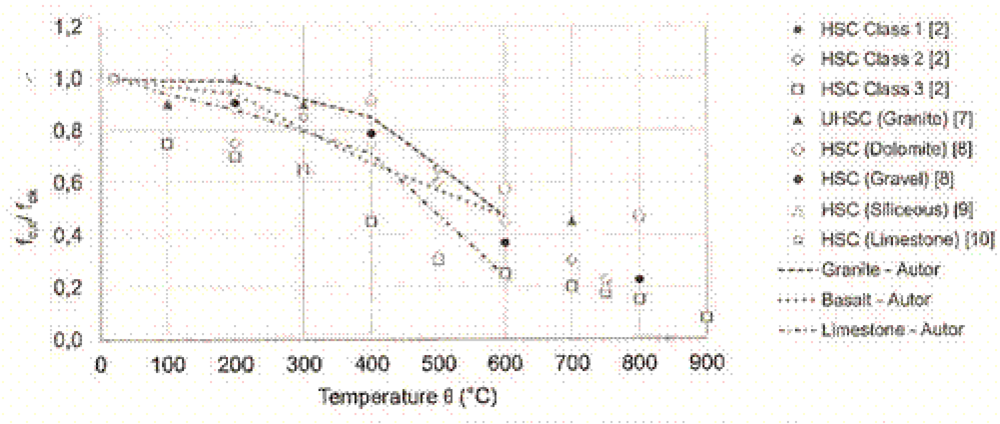


圖 19 高強度與超高強度混凝土在高溫下殘餘壓力強度折減係數

(6) Y. Li 探討聚丙烯纖維與鐵纖維在高溫下(30℃至 300℃)超高性能混凝土滲透性質，圖 20 顯示顯微鏡下超高性能混凝土火害後情形，(a)與(b)為高強度混凝土火害前後的差別(250℃)，(c)與(d)為聚丙烯纖維在 175℃下連續 20 小時候實驗前後情形，可看到聚丙烯纖維融化後留下的空間位置，會造成後續裂縫之產生，(e)與(f)為鐵纖維在 250℃溫度下實驗前後情形，因鐵纖維尚未達液化溫度，雖然會有小裂縫，但破壞性不大。

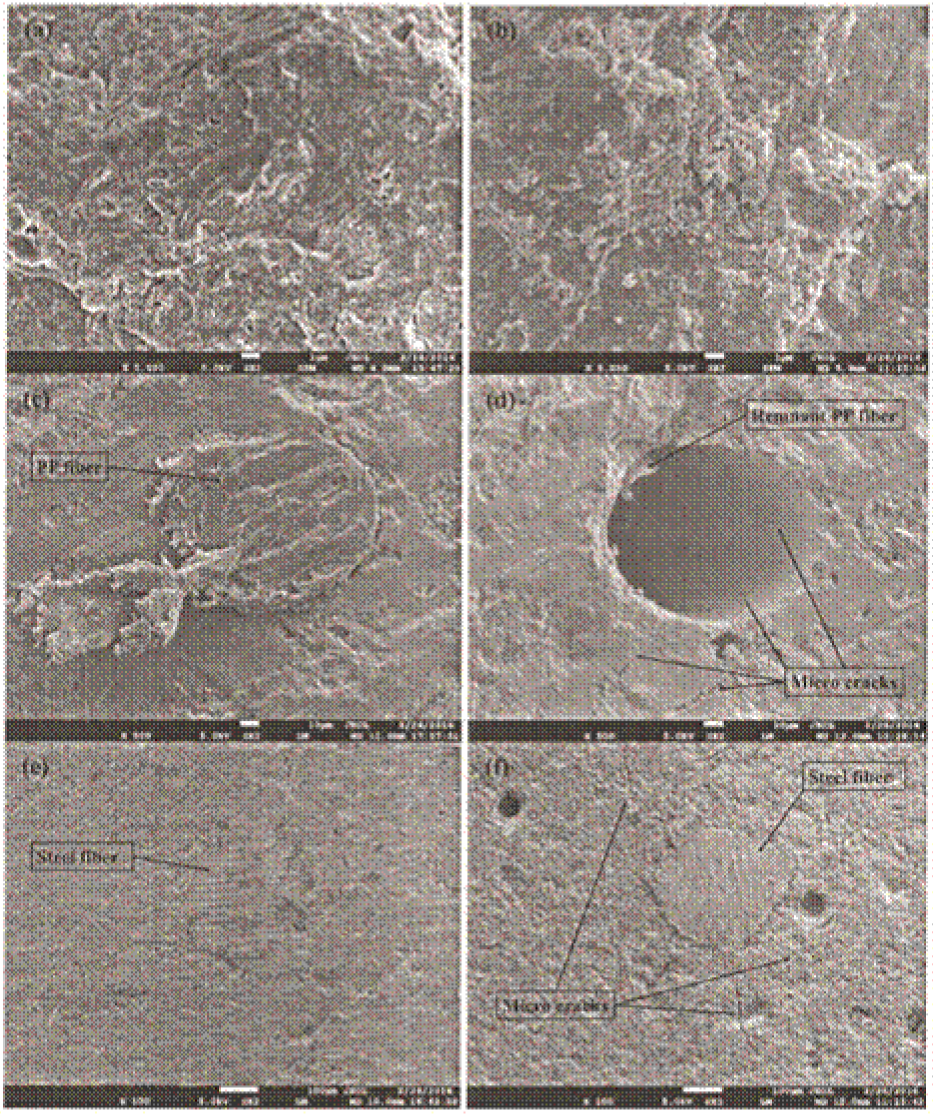


圖 20 顯微鏡觀察超高性能混凝土火害後情形

1.2 鋼材料方面包括高強度鋼及高強度螺栓，摘要部分可參考附錄二-2。

(1) D. A. Winful 研究高強度鋼(降伏強度在 460-700 N/mm^2)火害情形，實驗考量 3 種應變率 0.0002/min、0.001/min 及 0.005/min，以研究應變速率增高對於降伏強度之影響。增溫速率設定為 10℃/min，以避免溫度升高過快超過設定溫度，達到控制在±3℃以內。0.2%強度與 2%降伏強度取法如圖 21 所示，結果顯示線性強度(0.2%)與並不保守，反而線性強度(0%)較為適當。

有關降伏強度(2%)折減係數與彈性模數折減係數如圖 22 所示，與實驗數據與文獻資料比較，在 2%降伏強度折減係數上，Eurocode 不偏保守，但在彈性模數折減係數上，Eurocode 則略為保守。

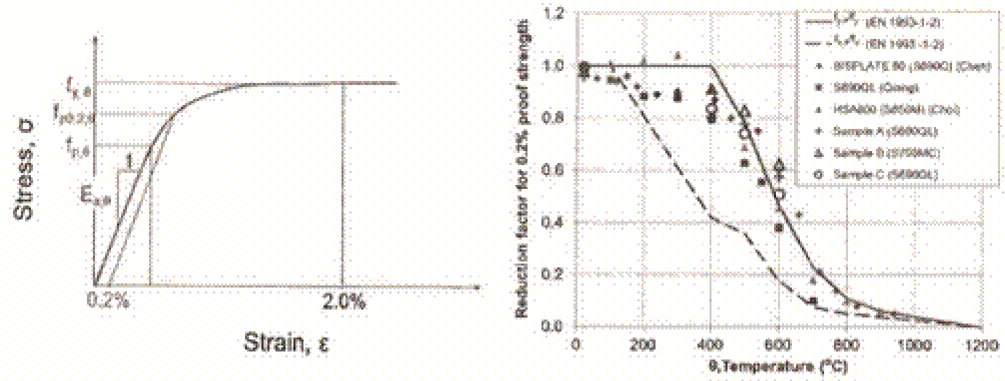


圖 21 應力應變關係與強度(0.2%)折減係數圖

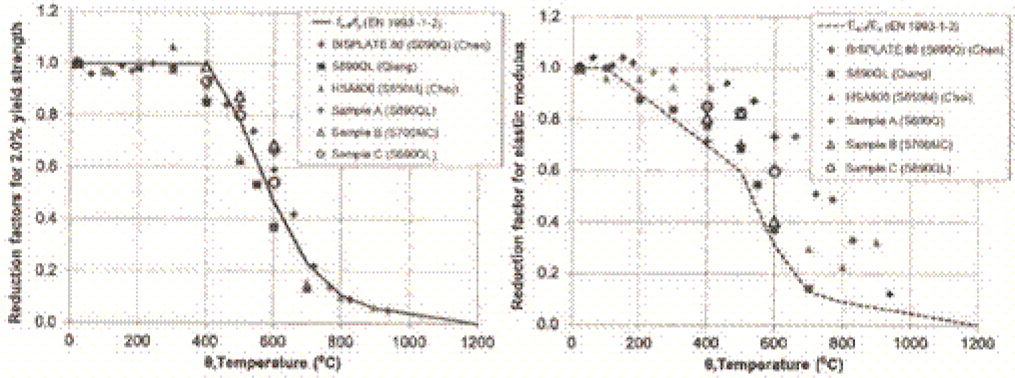


圖 22 降伏強度(2%)折減係數與彈性模數折減係數

(2) A. K. Kawohl 以實驗方法研究高強度螺栓在拉力與剪力合成作用下火害性質，因為接頭對於鋼結構的穩定非常重要，不只傳遞力量，還會影響構材內力。在火害中，螺栓於升溫時期會遭受到彎矩與剪力作用，在降溫時期因梁懸鏈線效應，會受到拉力與剪力作用，因此螺栓受火害時所具備的延展性是值得深入研究的。實驗設置試體角度如圖 23 所示，設計 30^{o} 及 45^{o} 兩種不同角度，以測試不同的合成拉力與剪力，0^{o} 除了測試純拉力外，並可作為比較用。

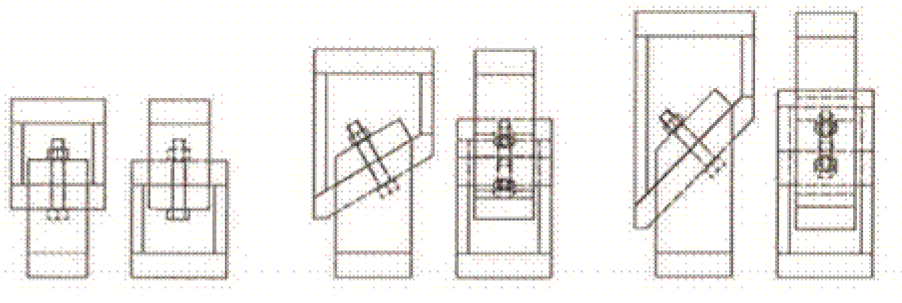


圖 23 實驗設置試體角度 0^{o}(左)、30^{o} (中)、及 45^{o} (右)

螺栓於 500℃下力量與位移實驗結果如圖 24 所示，3 種不同角度的測試結果差異很大，由其是在位移變化量(延展性)上，以 45° 試體最好，其他 2 角度試體幾乎無延展性。在破壞模式方面，常溫時的實驗結果，30° 試體為剪力破壞，但在 500℃時 0° 及 30° 試體為拉力破壞，45° 試體有 2 支為拉力破壞，1 支試體為剪力破壞，轉變的原因是在 500℃時鋼材料的液化現象所造成。

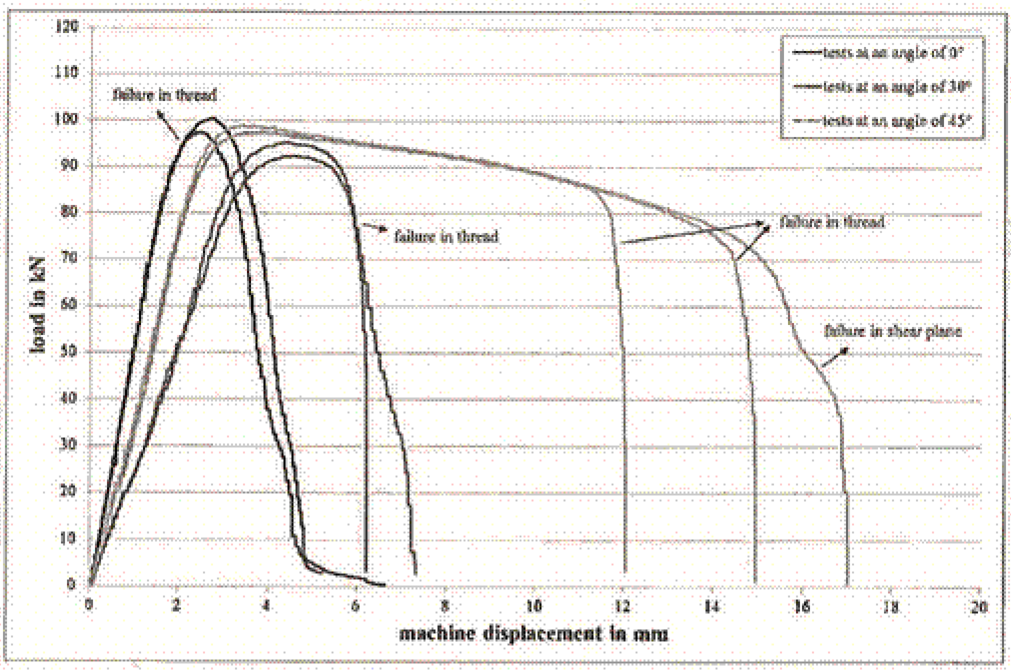


圖 24 螺栓於 500℃力量與位移實驗圖

有關實驗結果之材料折減因子與文獻比較如圖 25 所示，在 450℃以下，實驗結果較其他文獻高，在 450℃以上時則相反，是因為實驗時所用的應變速率較高($0.015mm^{-1}$)，而在高溫時由於潛變作用，應變速率對拉力強度有較大影響之故。

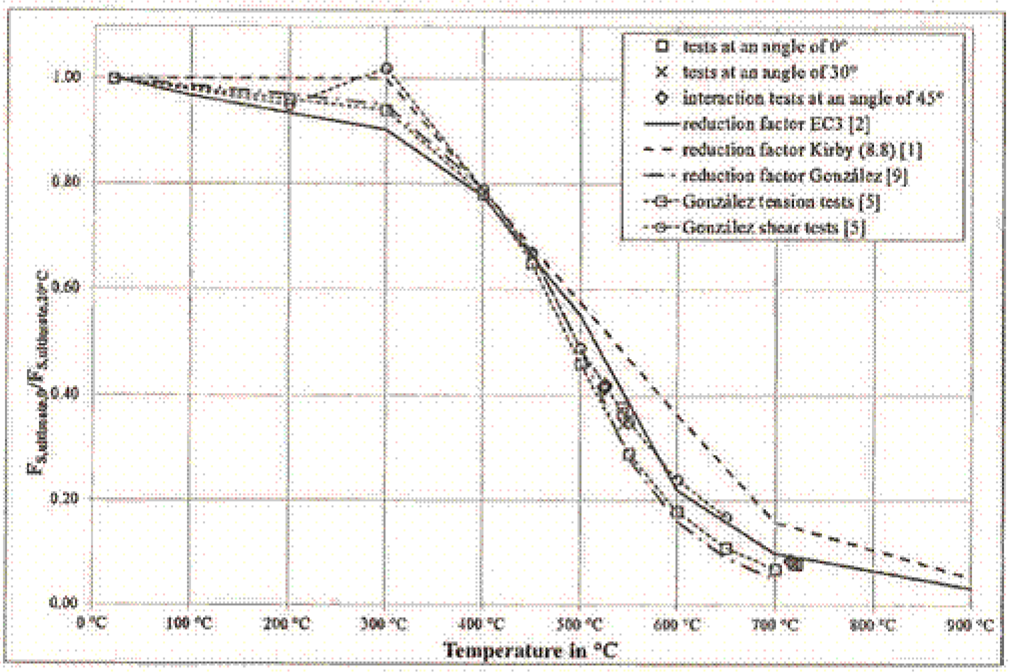


圖 25 材料折減因子與文獻比較

(3) M. Yahyai 以實驗方式探討火害後高強度螺栓 Grade 80 材料性質，包括應力應變曲線、極限強度、降伏強度及彈性模數。圖 26 顯示火害後螺栓應力應變關係圖，如圖所示，溫度越高，螺栓強度降低但延展性越好，由其當溫度超過 600℃時，更是明顯。

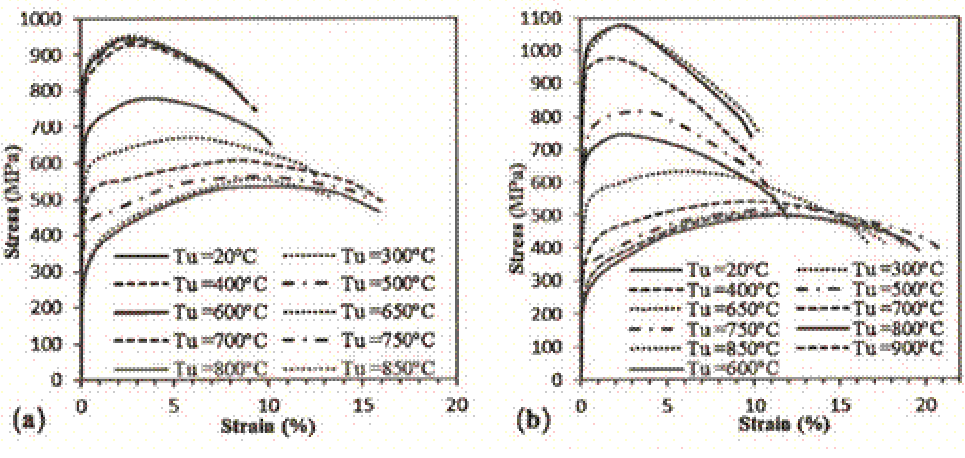


圖 26 火害後螺栓應力應變關係圖(a)M18(b)M22

螺栓火害後殘餘性質如圖 27 所示，無論極限拉力強度、降伏強度或彈性模數，都隨溫度升高而下降，且幾乎以 500℃為關鍵溫度，表示如果沒有超過此溫度，材料冷卻後性質與原來差不多，但若超過此溫度，冷卻後材料性質下降過多，不能再行使用。

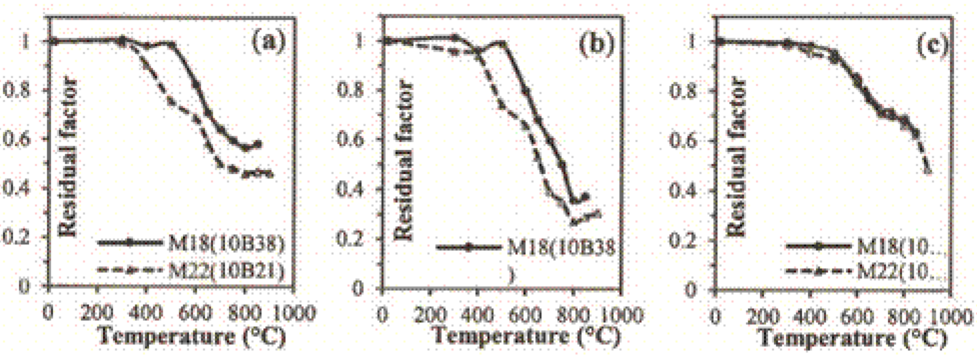


圖 27 螺栓火害後殘餘性質(a)極限拉力強度(b)降伏強度(c)彈性模數

1.3 木構造材料方面包括木材與積層材料碳化深度與開裂研究，因為近年來由於木構造在積層材料上及加工技術的突破，不再受限於柱梁構件尺寸，構築高層建築已不再是夢想，摘要部分可參考附錄二-3。

(1) R. Emberley 研究溫度對於積層材料破壞影響，最重要是所用的膠合材料，因為膠合材料失效與深入溫度有關。實驗顯示膠合材料在溫度 80 ℃以下是安全，但是當溫度超過 110℃以上時將失效。圖 28 顯示高溫下積層材膠合失效與木構造梁破壞情形，主要是由剪力造成膠結失效後，裂縫持續延伸擴大，最後造成木構造梁破壞。

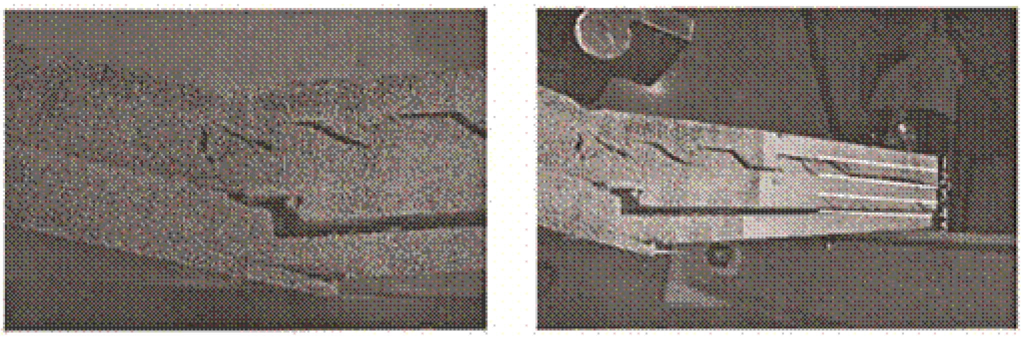


圖 28 高溫下積層材膠合失效與木構造梁破壞破壞情形

圖 29 顯示高溫下積層材脫層順序，開始時是產生剪力裂縫，再因裂縫點應力集中現象，造成裂縫延著膠合界面擴大，直到梁端或是遇到膠合材料比周圍木材強之處，裂縫才會轉向木材。

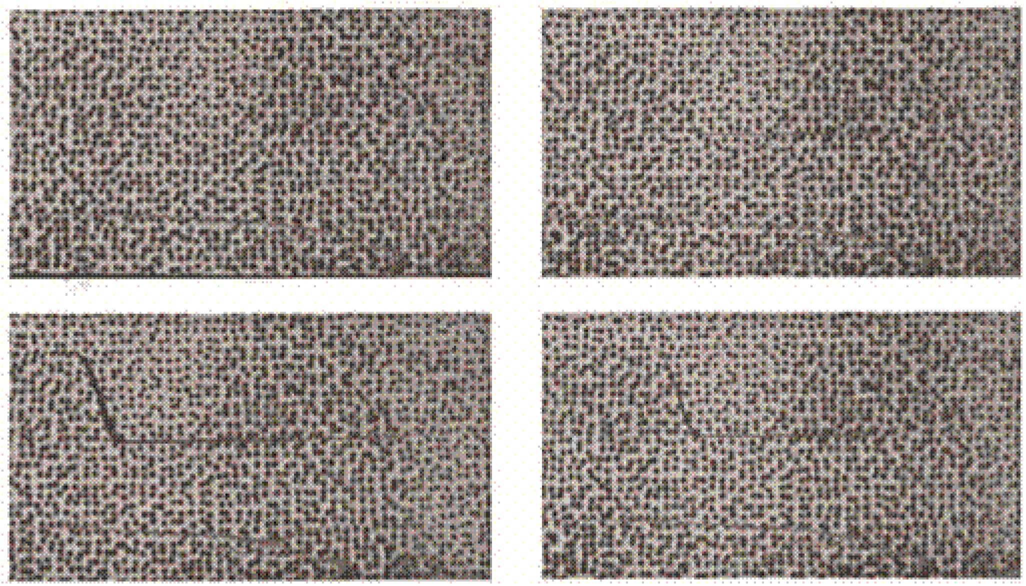


圖 29 積層材脫層順序(由左上順時針)

(2) N. Werther 以實驗研究影響木材碳化因素，探討內部濕度與不同溫度的關係，並提出簡單設計法計算碳化深度，及改進材料模式以適用於數值分析。圖 30 顯示木材表面溫度實驗結果比較，No 3 是低加溫速率實驗，No 7 是高加溫速率實驗，以探討熱傳導對於對表面碳化過程影響，實驗顯示加溫速率變大會增加碳化深度與碳化率，碳化深度則更與內部溫度深度有關。

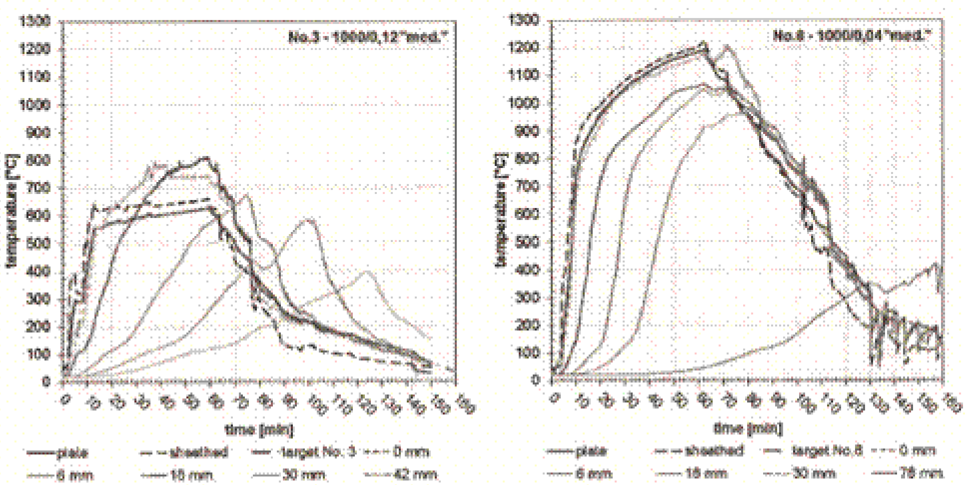


圖 30 木材表面溫度實驗結果比較(No 3 與 No 8)

根據 EN 1995-1-2 規範，碳化深度位置是依循 300℃等溫線，圖 31 顯示碳化深度與熱影響區域，高加溫速率(No 6-No 9)造成碳化深度較規範大約 2 倍，也比低加溫速率(No 1-No 4)所造成碳化深度大。不過在熱影響

區比較方面，高加溫速率造成熱影響區不一定較規範大，但平均比低加溫速率所造成熱影響區小。

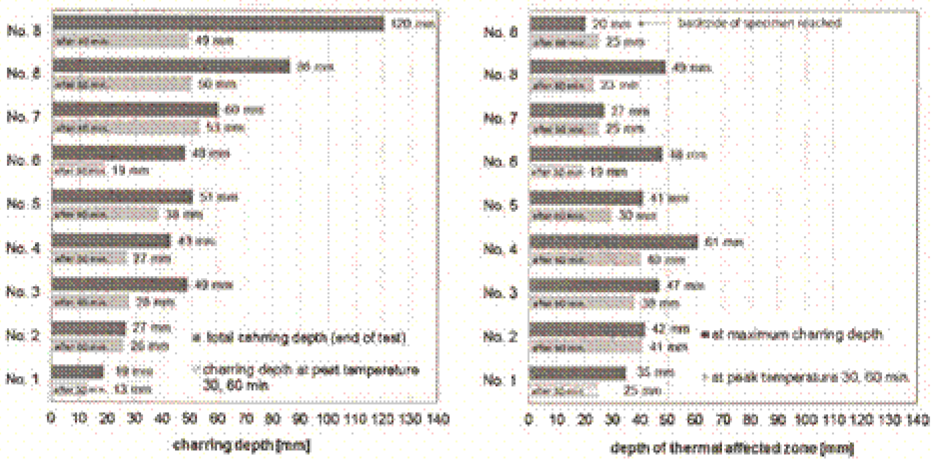


圖 31 木材碳化深度與熱影響區比較

圖 32 為木材 60 分鐘碳化結果，顯示火害溫度與碳化裂縫型態有關，高溫會導致較深裂縫，但較小的間隔，低溫則相反。有關木材濕度問題，實驗結果顯示，濕度若增加 1%，則碳化速率將降低 1%。

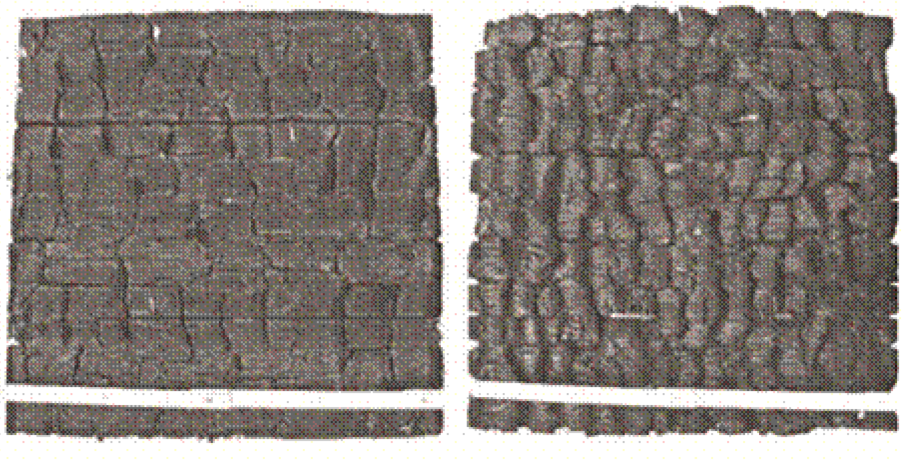


圖 32 木材 60 分鐘碳化結果(左-No 2 低溫測試，右-No 7 高溫測試)

1.4 防火被覆方面包括不同防火被覆性能，及複合載重下防火被覆破壞模式實驗，摘要部分可參考附錄二-4。

(1) A. Lucherini 以實驗方法研究不同防火被覆對鋼結構耐火之影響，對於不同火災情境，受熱狀況不同，受熱速率不同，防火被覆的效果就會有明顯差異。圖 33 顯示防火被覆受熱膨脹的 4 個階段(如圖中以垂直虛線分成之 4 部分)，與 4 個狀態轉換點(如圖中以圓圈表示)，其中 Activation

Point 表示防火被覆受溫開始膨脹之處，此時其阻熱性增加，至 End of Reaction Point 表示防火被覆結束膨脹，此時阻熱性最高，隨後阻熱性慢慢降低，直至降到 Steady Point 後，阻熱性大約保持穩定。

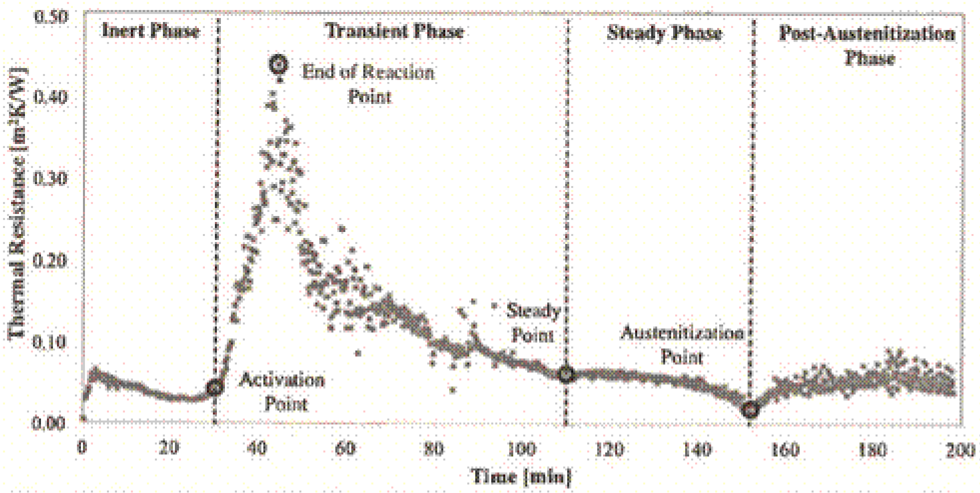


圖 33 防火被覆受熱膨脹的 4 階段與 4 個轉換點

圖 34 與圖 35 顯示溶劑性及水性防火被覆在 5 種不同爐溫(受熱率)下膨脹情形，由圖可知，水性防火被覆分布較為平均，依照受熱率不同產生反應，比溶劑性防火被覆快速反應，效果較為好，亦即溶劑性防火被覆對於受熱率小的火害提早反應較不適當；不過，溶劑性防火被覆在受熱率高的火害下，有較高的阻熱性。

另外，由實驗結果可知，於不同火害環境下，不同防火被覆材料其性能表現就不同，但目前設計規範對於防火被覆有些限制，無法反應這類結果，未來更應進行相關研究，使不同產品能有相對應的火害使用情境。

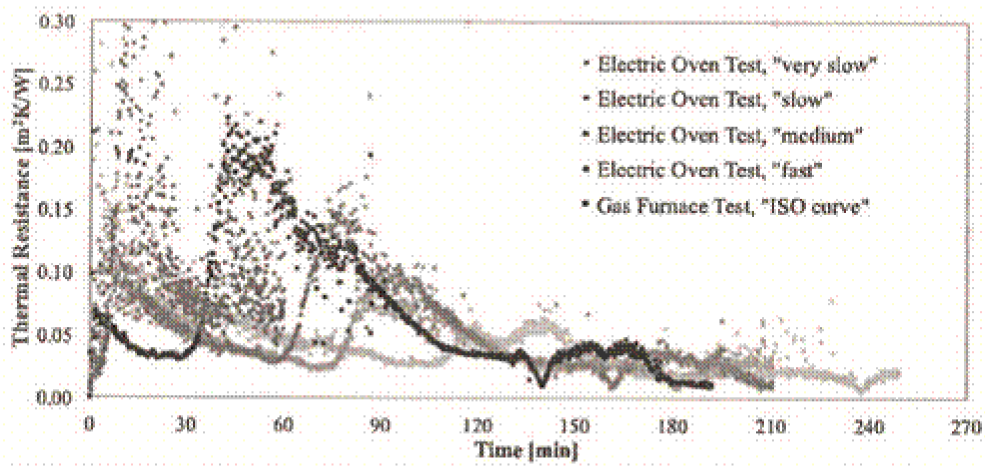


圖 34 溶劑性防火被覆在 5 種不同爐溫(受熱率)下膨脹情形

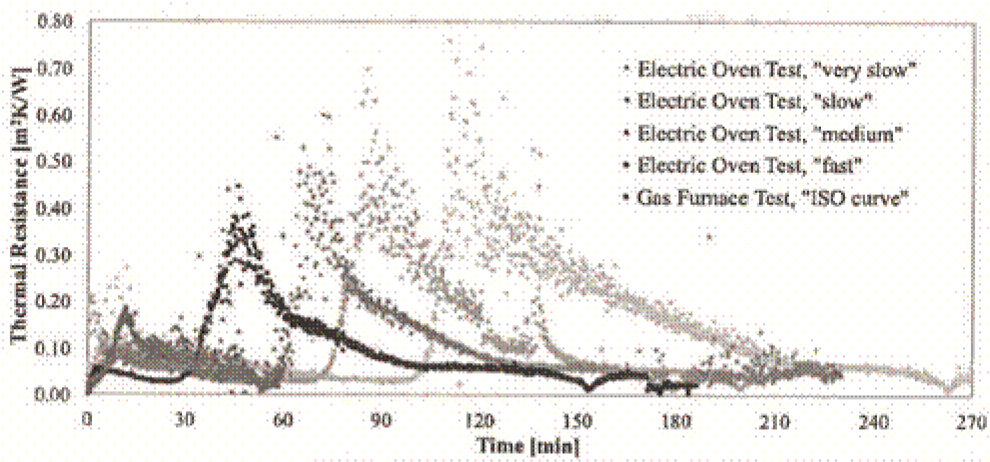


圖 35 水性防火被覆在 5 種不同爐溫(受熱率)下膨脹情形

(2) S. W. Chen 以實驗方法探討在複合載重下鋼柱使用不同防火被覆的破壞模式，包括水泥防火塗料與膨脹型防火被覆，圖 36 與圖 37 表示鋼柱塗上水泥防火塗料及膨脹型防火被覆實驗破壞情形，其中Φ 為層間變位角，由圖可知，水泥防火塗料由於厚度較大，因此裂縫產生較早，Φ =0.0041 就發生，如圖 36(a)，裂縫逐漸發展，直到Φ =0.0449 鋼梁底部壓力側翼板挫屈，塗料才發生剝落，如圖 36(d)所示。

圖 36 水泥防火塗料受單向載重破壞情形(Φ 為層間變位角)

膨脹型防火被覆厚度較薄，直到層間變位Φ =0.0241 才開始有小裂縫，如圖 37(a)，至鋼梁底部壓力側翼板挫屈Φ =0.0483 發生較多水平小裂縫，層間變位達Φ =0.0723 裂縫發展至相互連結，如圖 37(c)，直到實驗停止Φ =0.0901，如圖 37(d)，此時層間變位角為水泥防火塗料實驗之 2 倍大。

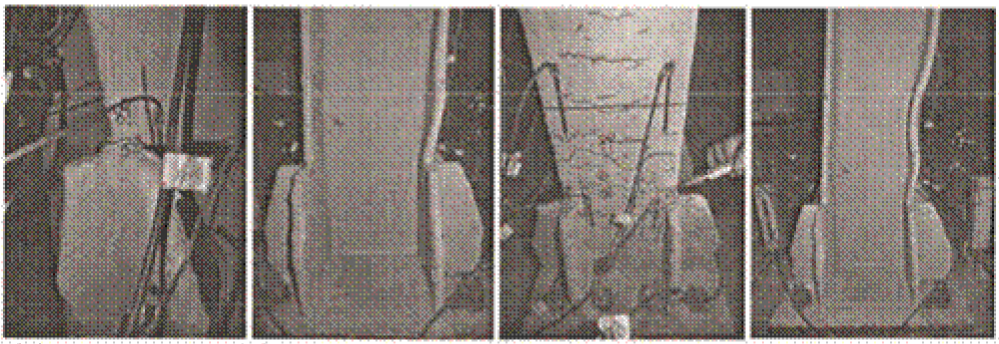


圖 37 膨脹型防火被覆受單向載重破壞情形(Φ 為層間變位角)

建築結構受到橫向作用力時，如地震力、風力或爆炸力，會造成鋼柱防火被覆產生裂縫，這些裂縫將降低防火被覆的耐火性能，另外，防火被覆的厚度也是裂縫容易產生關鍵原因之一，在設計複合災害載重時應予以考量。

2、大型結構實驗屋火害試驗：

自 2003 年英國 Cardington 多樓層鋼構屋火害實驗計畫以來，各國研究單位陸續進行相關實驗，2009 年美國加州聖地牙哥 Englekrik 實驗研究中心進行 3 年 5 層樓實尺寸震後火災實驗計畫，捷克於 2015 年進行 4 層樓 Tisova Fire Test 實驗(摘要參考附錄二-5-1)，這些實驗數據經過多年整理，仍繼續在各國際期刊及研討會中發表實驗結果及數值分析，如梁柱接頭模擬及破壞模式，和樓版薄膜效應等，這些對本所於今年即將進行鋼構屋火害實驗，都是很好的參考資料。

2.1 大型結構實驗方面包括樓版及複合鋼梁火害結構行為研究，及樓版薄膜效應研究，相關文章摘要可參考附錄二-5-2 至 5-5。

(1) L. Choe 發表美國國家標準技術研究所(National Institute of standards and Technology, NIST)鋼梁局部火害實驗，以評估瓦斯爐的熱釋放率對鋼梁試體，及局部火害對於鋼梁耐火行為與承載力的影響。圖 38 為實驗設置與熱偶線量測點佈設位置圖，圖 39 為鋼梁實驗結果，包括破壞模式及冷卻後狀態。實驗結果及數據會用來發展並校正數值分析結果，以進行後續評估建築構件受局部火害影響。未來研究包括探討不同邊界條件，如軸向及旋轉束制，與加熱速率對鋼梁之影響。

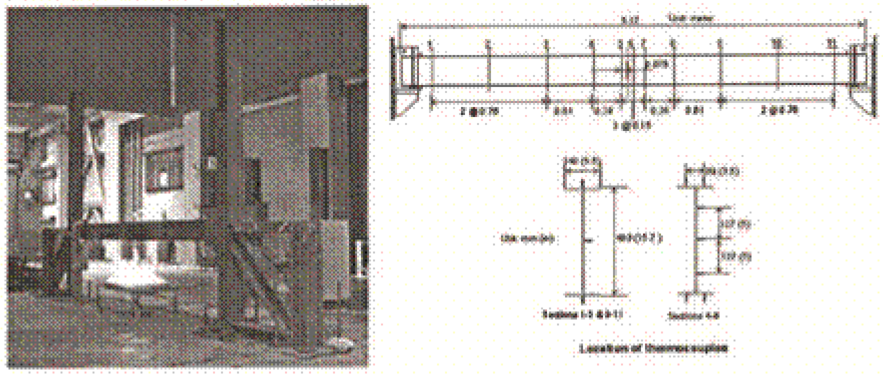


圖 38 實驗設置與量測點位置圖

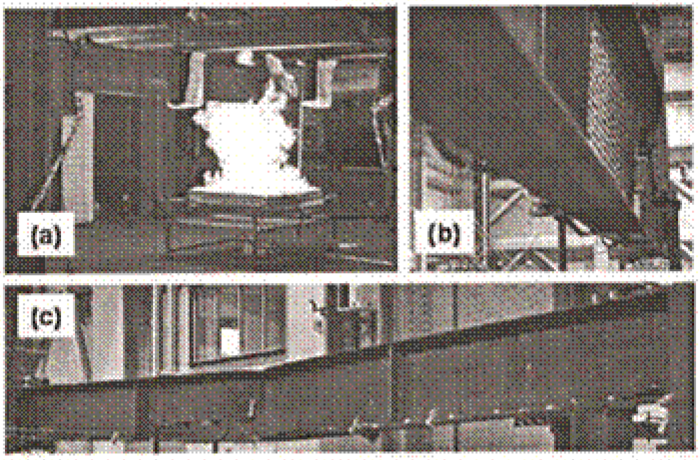


圖 39 實驗結果(a)鋼梁破壞模式(b)鋼梁側向挫屈(c)鋼梁冷卻後狀態

(2) F. Alfawakhiri 以實驗方式，探討不同載重比與束制對鋼梁與複合梁防火時效，試體共 16 支。實驗結果為在不同載重比與束制條件下，以量化方式呈現破壞溫度，如圖 40 之表列，圖 41 為未束制鋼梁試體火害前後比較。實驗結果是低載重與束制可增加鋼梁耐火時效，但較令人意外的是，複合梁耐火時效比鋼梁差，這可能是只探討破壞溫度所造成，須再行檢驗。

Load Intensity, %	For Restrained Non-Composite Beams, °F (°C)	For Unrestrained Non-Composite Beams, °F (°C)	For Restrained Composite Beams, °F (°C)	For Unrestrained Composite Beams, °F (°C)
100	1263 (684)	1220 (660)	1132 (611)	1056 (569)
80	1293 (701)	1274 (690)	1166 (630)	1113 (601)
60	1348 (731)	1379 (748)	1271 (688)	1255 (679)
40	1447 (786)	1488 (809)	1448 (787)	1438 (781)

圖 40 鋼梁與複合梁在不同載重比與束制條件之破壞溫度

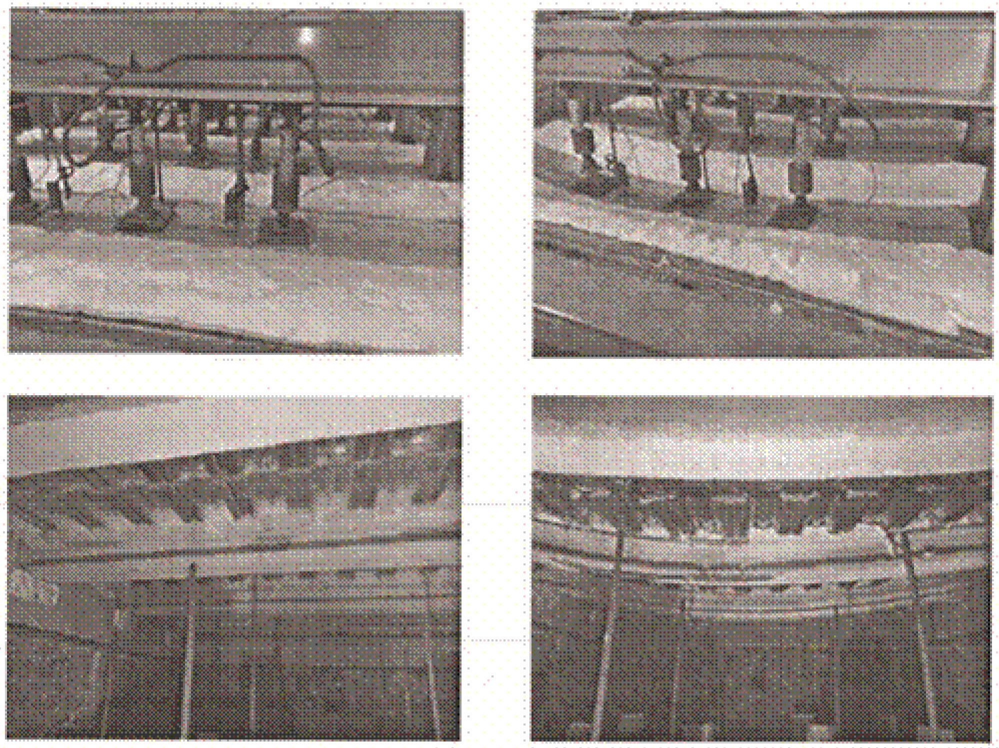


圖 41 未束制鋼梁試體火害前(左)與火害後(右)比較

(3) F. Quichaud 以影響線方式探討樓版受火害產生大變位，形成拉力薄膜效應之破壞模式，影響線模式發展如圖 42 之(a)與(b)，可能之破壞模式如圖 42 之(d)、(e)與(f)。這是一種簡略預測樓版破壞模式方法，不過對於樓版受高溫火害，使得內部鋼筋溫度超過 500℃，或是樓版為正方形形狀，都不適用，因此仍須進一步研究。

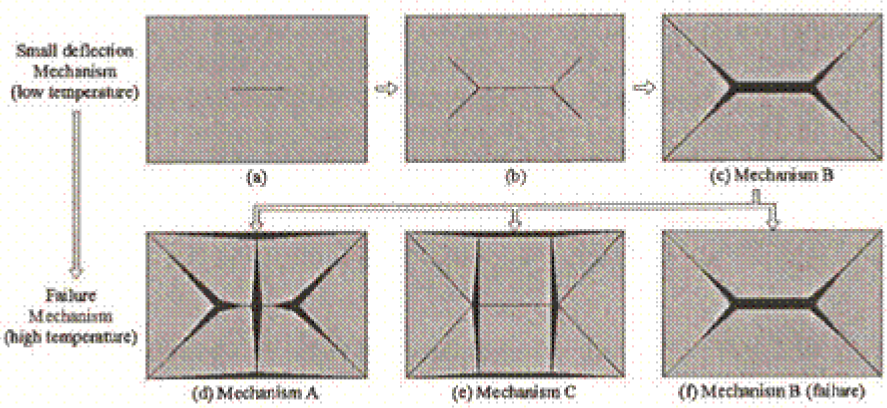


圖 42 影響線模式發展(a, b)與可能破壞模式(d, e, f)

(4) R. R. Sun 以數值方法分析混凝土樓版受局部火害產生大變形，以了解樓版結構在局部火害中的破壞行為，樓版設計平面如圖 43 所示，房屋起火點位置於 bay 7。圖 44 顯示房屋隔間受大變形與時間關係結果，由圖

可知，Bay 6 垂直變形最大，應該是受到樓版產生高溫梯度之影響。另外，樓版變形隨時間呈現來回震盪，是由於局部火災在各個隔間產生不均勻溫度，加上火的移動產生。而且，這類如辦公室隔間造成的火害，溫度增加速率比 ISO 標準低，顯示傳統結構防火工程所設計之樓版過於保守。

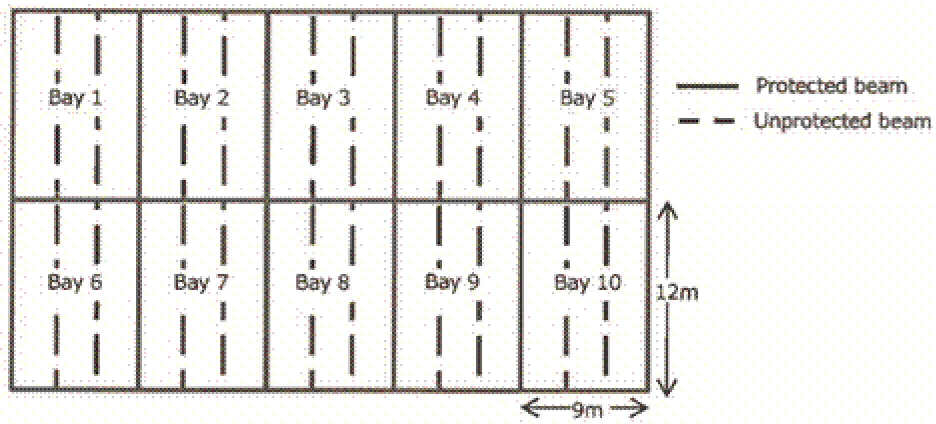


圖 43 樓版設計平面圖

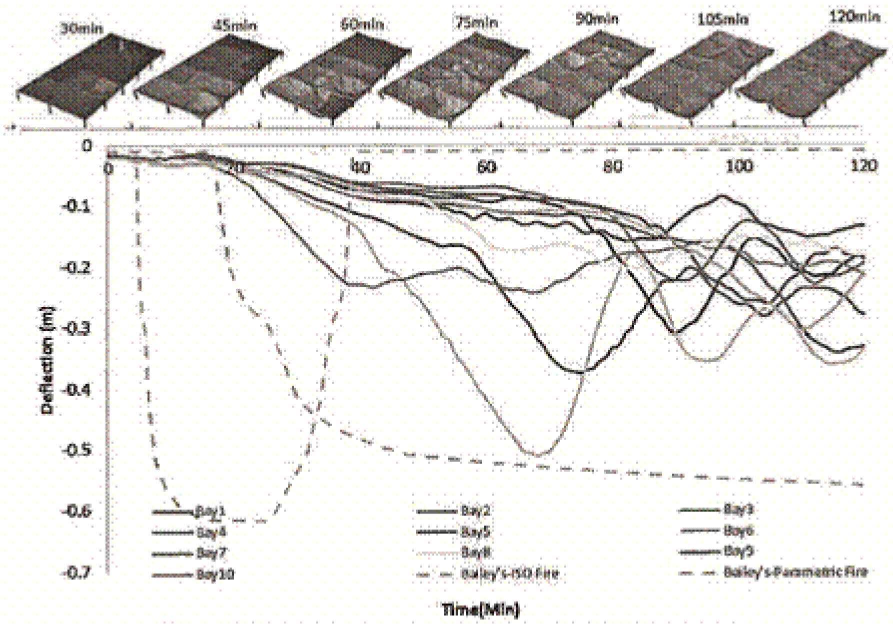


Figure 8. Deflection developments within the compartment.

圖 44 房屋隔間受大變形與時間關係

2.2 實驗量測設備與方法方面，因結構火害實驗受限於高溫環境，許多重要的數據難以量測，如結構變形、位移及桿件內力等，因此發展耐高溫且穩定的量測方法與設備非常重要。本次發表研究中，有光學感測與數位影像 2 種，雖然都不是新技術，但是因為精度提高，也值得參考，簡述如下(摘要詳見附錄二-6)：

(1) 光學感測法：Y. Bao 利用 2 種光纖感測技術，分別量測溫度與應變，且都具有耐高溫性質，可達 1050℃。量測溫度是用布里安散射光纖，Pulse pre-pump Brillouin Optical Time Domain Analysis (PPP-BOTDA)，如圖 45 所示，為分布式光纖感測技術，須分段求取平均值，過去因為精度不高，最小段只達 2 公尺，無法用於結構實驗，只能用於大面積防災監測。近年來儀器精度提高，已可縮小至 2 公分，雖然對於結構實驗來說，精度仍不足，但是能耐高溫的特性，可嘗試用於結構防火實驗。在應變量測上，是以干涉原理 Extrinsic Fabry-Perot Interferometrci (EFPI)進行，如圖 46 所示，應變量測可達 35300με。

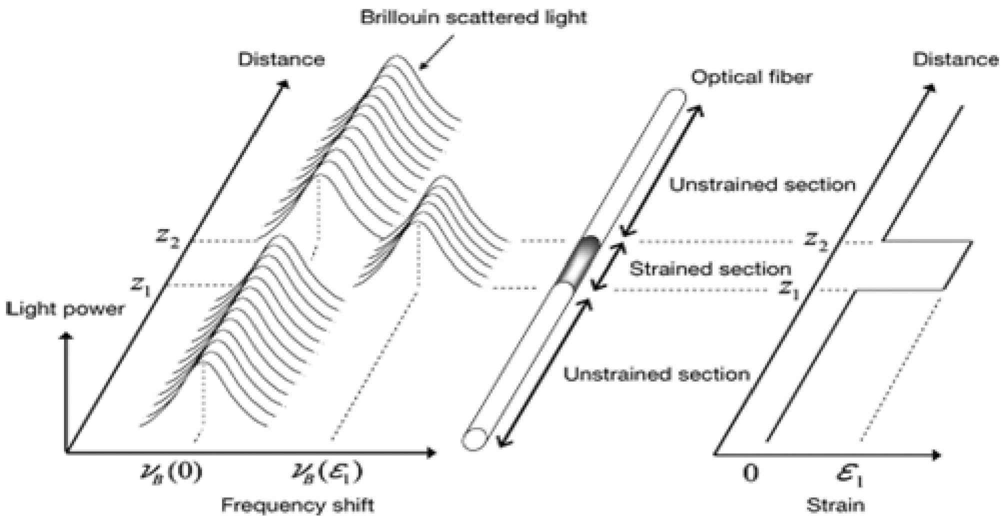


圖 45 Pulse pre-pump Brillouin Optical Time Domain Analysis (PPP-BOTDA)原理

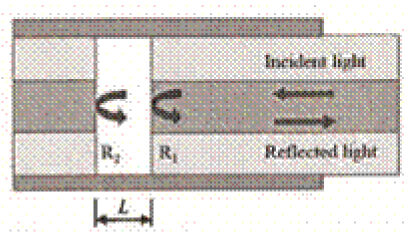


圖 46 Extrinsic Fabry-Perot Interferometrci (EFPI)原理

(2) 數位影像法：J. L. Hodges 研究熱影像和數位影像相關法 Thermographic Digital Image Correlation (TDIC) ，利用 2 台 CCD 照相機，1 台 IR 照相機，同時量測位移與溫度，實驗設置如圖 47 所示。

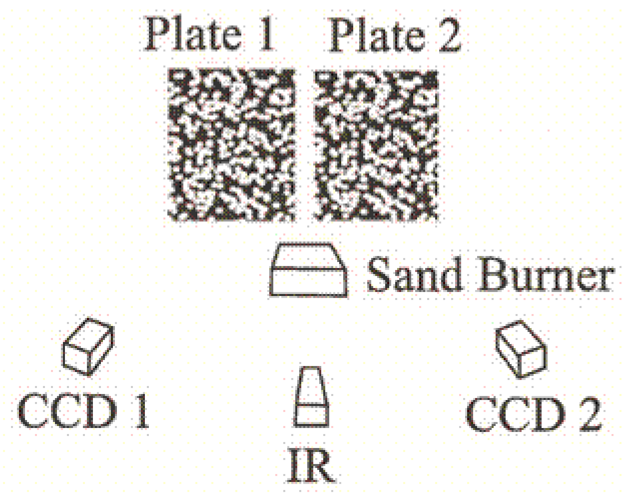


圖 47 熱影像和數位影像相關法實驗量測設置

3、數值分析軟體

數值分析方法主要是用來輔助結構火害實驗的不足，獲得火害實驗不易量測的數據，以擴大實驗的研究成果。泛用型有限元素分析軟體如 ABAQUS，ANSYS，可應用於各類產業如機械、電子，土木建築等，舉凡金屬、複合材料、鋼筋混凝土，結構應力、振動、聲學、熱傳、流體皆可分析。

這類軟體分析能力雖然強大，卻也複雜不易學習。對於研究結構火害來說，趨勢觀察及預測同樣重要，為了節省時間與計算花費，建議可選用其他軟體。研討會中不乏其他特定性軟體，如模擬結構與大地工程系統受地震反應的 OpenSees，或專門使用於混凝土及鋼筋混凝土結構的 ATENA，還有混合試驗系統研究程式 OpenFresco，建築結構火害 SAFIR 與 LS-DYNA，都可供本所防火實驗中心參考。

目前數值分析方法所遭遇困難，除了軟體購買費用高外，使用者不會將問題簡化也是原因之一，一般多只使用線性元素，使得所建立的模型過於繁複，網格過多，造成運算時間過久且不易收斂，由其是模型中含有 2 種以上不同材料，如鋼、螺栓及混凝土材料，其界面設定複雜，都是數值分析結果與實驗結果誤差來源。

為了讓使用者容易上手，也希望能節省運算時間，最簡單的方式是發展新元素，將複雜的材料性質直接寫入元素中，目前新元素發展有 2 方向，簡述如下(摘要可參考附錄二-7)：

(1) 針對特定問題所發展新元素：G. Quan 為探討局部挫屈而發展 component based connection and buckling element 元素，設計原理如圖

48 所示，用於 VULCAN 數值分析軟體，使用影響線原理，預測火害時梁腹板剪力挫屈，與梁翼板挫屈現象。

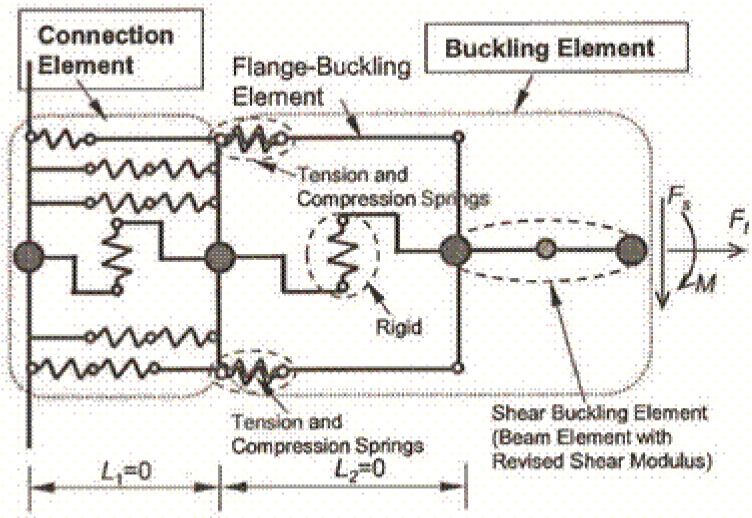


圖 48 component based connection and buckling element 元素設計原理

(2) 發展能讓熱傳與力學分析同時進行運算的元素：P. Woelke 發展 WAifire 模型，主要是供有延展性的金屬材料使用，以探討高溫潛變與材料軟化性質。

三、心得與建議

透過這次參訪了解，國際上頂尖大學除了領導學術方向外，同時也非常強調教學，訓練學生的方式是結合專業與通識教育兩方面，亦即不只教授課堂知識，還要傳授教育理念與對自然環境關懷。真正的教育家是辦教育，而不是爭排名，真正的學者應該是好奇與探索，而不是算論文數量。在與 Garlock 教授訪談中不斷感受到她真心為學生的付出，就算在承擔學校行政與尋求資源的壓力下，仍非常注重學生的教學，聽她談如何設計課程內容的熱情，聯絡校外教學及籌措經費的辛勞，再看到學生最後學習成果的展現，都是令人印象深刻的。

在建築防火專業上，Garlock 教授謙虛表示她也是受到一些資深教授的啟發與引導，如密西根州立大學 Venkatesh K. R. Kodur 教授的鼓勵，給予她信心與肯定，在研究領域上協助她如何看大方向與趨勢發展，了解目前各領域不足之處，並尋求與世界各大學及其他研究單位合作，同時參加研討會學習組織運作，現在的她才有能力承辦本屆結構火災安全國際研討會。也因為她有如此豐富背景，在訪談中才能對各領域問題有獨特的見解，提供本所參考。

參加本屆結構火災安全國際研討會，除了蒐集建築結構防火相關資料，對於目前國際上結構防火研究進程，如材料研發，實驗技術與方法的應用，數值軟體的選擇與使用，皆能有充分了解與體認，對本所新建鋼構屋火害實驗計畫，我國建築結構耐火規範之研訂及防災規劃，及提升建築防火安全等公共安全議題，均有莫大助益。

本次參訪考察建議如下：

1. 有鑑於國際間仍缺乏不同溫度下鋼與混凝土材料基本性質資料，建議可考量與各大學及技師公會合作，共同規劃實驗研究，建立一般材料與高強度材料基本性質資料庫。

2. 進行大型實驗計畫非常不容易，不但經費龐大且費時甚久，在實驗完成後，可針對細節進行局部實驗，或用數值分析進行驗證，再以數值分析求得無法於實驗中獲得的資料。本所台南防火實驗中心實尺寸鋼構屋即將完成，並進行一系列相關實驗，非常不容易，建議可參考其他國家案例，配合數值分析方法，規劃中長程研究計畫，以擴大研究成果。

3. 由於實驗技術進步，發展出新的高溫量測方法，建議本所台南防火實驗中心高溫複合爐可參考規劃適當的量測設備，無論是光學感測或是數位影相法，以因應大型構架火害實驗量測設備不足。

4. 數值分析方法可輔助大型結構火害實驗不足，建議依據本所實驗設備特性，與我國材料性質，逐漸發展以建立一套配合本所設備的分析模式，以節省大型實驗經費與時間。

5. 各國由於實驗設備之限制，不容易進行複合型災害研究實驗計畫，本所實尺寸鋼構實驗屋即將完成，建議可配合國家地震中心台南實驗室，進行相關實驗計畫。

6. 木構造方面由於積層材料與技術的突破，加上木材是屬於低碳材料，因此作為未來下一世代的建築材料是指日可待，也是國際上積極發展之新領域。但因目前規範有 4 層樓限制，且防火規範專章仍未完成，建議先完成基本木構造規範，再規劃進行中高層建築相關研究。

附錄一

第 9 屆結構火災安全國際研討會(Structures in Fire, SiF) 議程

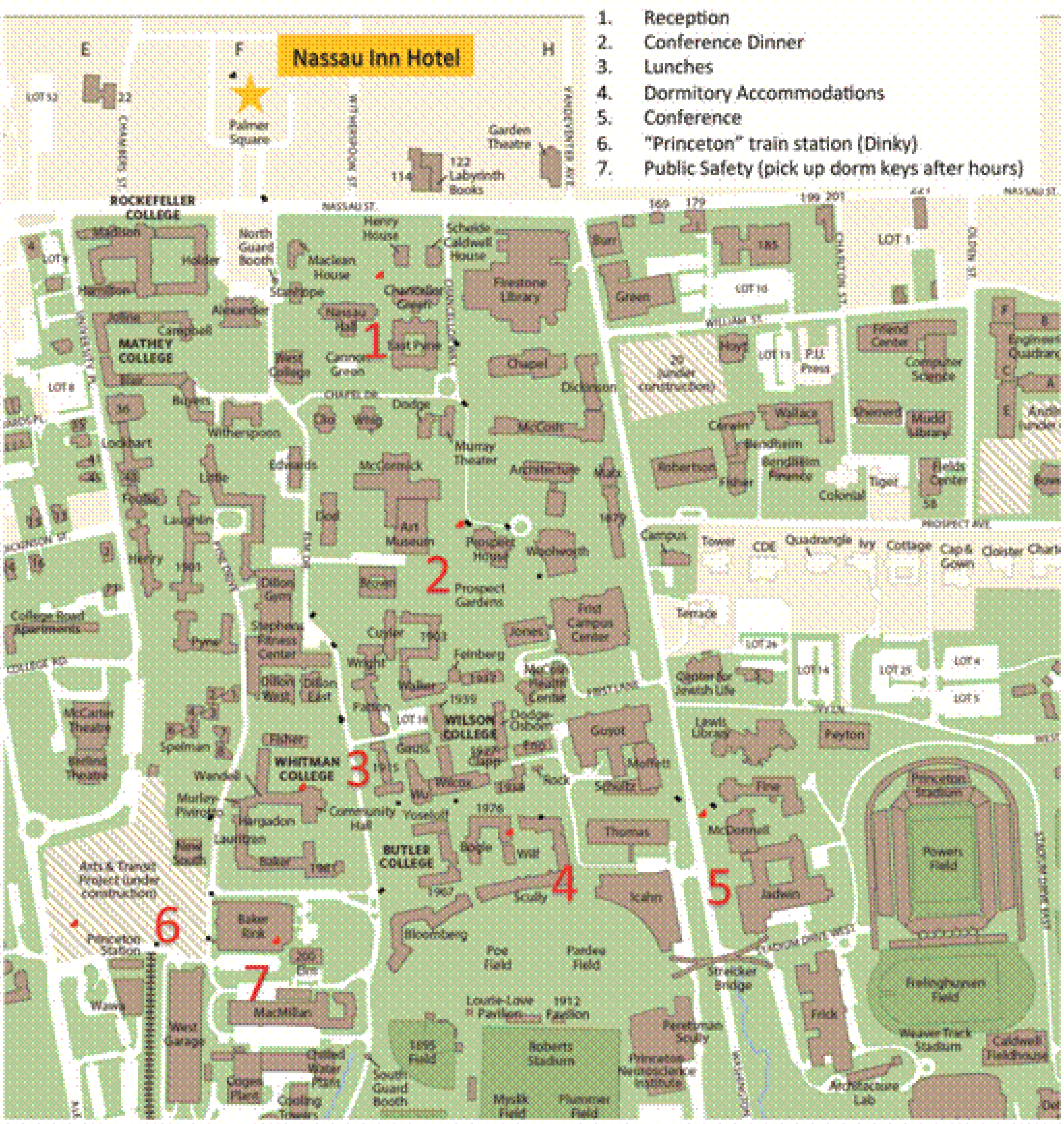
1. 簡要議程
2. 詳細議程
3. 海報展示題目

Program at a Glance

9th International Conference on Structures in Fire

Princeton University, June 8 - 10, 2016

Tuesday, June 7, 2016		
18:00 - 20:00	Registration and Opening Reception *Sponsored by School of Engineering and Applied Science, Princeton University*	*Chancellor Green Rotunda*
Wednesday, June 8, 2016		
7:00 - 8:00	Registration and Continental Breakfast	*Gallery Outside of McDonnell Hall A01/A02*
8:00 - 8:30	Opening	*McDonnell Hall A02*
8:30 - 9:30	Session 1-A: Numerical Modeling	*McDonnell Hall A02*
9:30 - 10:00	Coffee Break / Poster Session	*Gallery Outside of McDonnell Hall A01/A02*
10:00 - 11:45	Session 1-B.1: Concrete Columns and Walls Session 1-B.2: Steel Connections and Floor Beams	*McDonnell Hall A02* *McDonnell Hall A01*
11:45 - 13:00	Lunch	*Community Hall, Whitman College*
13:00 - 14:45	Session 1-C.1: Concrete Slabs & Beams Session 1-C.2: Metal Structures	*McDonnell Hall A02* *McDonnell Hall A01*
14:45 - 15:15	Coffee Break / Poster Session	*Gallery Outside of McDonnell Hall A01/A02*
15:15 - 16:45	Session 1-D.1: Timber Session 1-D.2: Numerical Modeling	*McDonnell Hall A02* *McDonnell Hall A01*
18:00 - 20:00	Reception *Co-sponsored by American Institute of Steel Construction (AISC) and Underwriters Laboratories(UL)*	*Chancellor Green Rotunda*
	Thursday June 9, 2016	
7:00 - 8:00	Registration and Continental Breakfast	*Gallery Outside of McDonnell Hall A01/A02*
8:00 - 9:15	Session 2-A: Concrete Slabs & Beams	*McDonnell Hall A02*
9:15 - 9:30	1-minute Oral "Commercials" of Posters	*McDonnell Hall A02*
9:30 - 10:00	Coffee Break/Poster Session	*Gallery Outside of McDonnell Hall A01/A02*
10:00 - 11:45	Session 2-B.1: Concrete Spalling Session 2-B.2: Bridges	*McDonnell Hall A02* *McDonnell Hall A01*
11:45 - 13:00	Lunch	*Community Hall, Whitman College*
13:00 - 14:45	Session 2-C.1: Concrete Material Characterization Session 2-C.2: Experimental Methods + Traveling Fires	*McDonnell Hall A02* *McDonnell Hall A01*
14:45 - 15:15	Coffee Break/Poster Session	*Gallery Outside of McDonnell Hall A01/A02*
15:15 - 17:00	Session 2-D.1: Fiber Reinforcement and Strengthening Session 2-D.2: Fire Protection Materials	*McDonnell Hall A02* *McDonnell Hall A01*
19:00 - 22:00	Dinner	*Prospect House*
	Friday, June 10, 2016	
7:00 - 8:00	Continental Breakfast	*Gallery Outside of McDonnell Hall A01/A02*
8:00 - 9:15	Session 3-A: Timber	*McDonnell Hall A02*
9:15 - 9:45	Coffee Break / Poster Session	*Gallery Outside of McDonnell Hall A01/A02*
9:45 - 11:00	Session 3-B.1: Applications of Fire Safety Session 3-B.2: Composite Columns	*McDonnell Hall A02* *McDonnell Hall A01*
11:00 - 11:30	Coffee Break / Poster Session	*Gallery Outside of McDonnell Hall A01/A02*
11:30 - 12:30	Session 3-B.3: Probabilistic Approaches Session 3-B.4: Steel Material Characterization	*McDonnell Hall A02* *McDonnell Hall A01*
12:30 - 13:45	Lunch	*Community Hall, Whitman College*
13:45 - 15:15	Session 3-C: Steel Structures	*McDonnell Hall A02*
15:45 - 16:30	Closing Ceremony	*McDonnell Hall A02*


1. Reception
2. Conference Dinner
3. Lunches
4. Dormitory Accommodations
5. Conference
6. "Princeton" train station (Dinky)
7. Public Safety (pick up dorm keys after hours)
Nassau Inn Hotel
Palmer Square
ROCKEFELLER COLLEGE
MATHEY COLLEGE
WHITMAN COLLEGE
WILSON COLLEGE
BUTLER COLLEGE
Firestone Library
Chapel
Prospect Gardens
Art Museum
Frick
Jadwin
Princeton Stadium
Powers Field
Princeton Station
MacMillan
Poe Field
Pardee Field
Roberts Stadium
Lewis Library
Peyton
McDonnell
Fine
Icahn
Scully
Bloomberg
Streicker Bridge

Detailed Program

9th International Conference on Structures in Fire

Princeton University, June 8 - 10, 2016

Time	Title	Authors	Proceedings Page
	Tuesday, June 7, 2016		
18:00 - 20:00	**Registration and Opening Reception (*Chancellor Green Rotunda*)**	**Sponsored by School of Engineering and Applied Science, Princeton University**	
	Wednesday, June 8, 2016		
7:00 - 8:00	**Registration and Continental Breakfast (Gallery Outside of McDonnell Hall A01/A02)**		
8:00 - 8:30	**Opening (McDonnell Hall A02)**		
8:30 - 9:30	**Session 1-A: Numerical Modeling (McDonnell Hall A02)** Co-Moderators: Jean-Marc Franssen & Martin Gillie		**Proceedings Page**
8:30 - 8:45	CONSTITUTIVE MODELLING FOR FIRE ENGINEERING PURPOSES - THE CHALLENGE OF MODELLING CREEP IN AN APPROPRIATE WAY	*Manfred Korzen**	608
8:45 - 9:00	RESULTS OF A POST TEST ROUND ROBIN OF THE CALCULATED RESPONSE OF A LOADED STEEL BEAM TO A FURNACE TEST	*David Lange*, Lars Boström*	1000
9:00 - 9:15	NUMERICAL MODELLING OF LOAD-INDUCED-THERMAL-STRAIN OF PRESTRESSED CONCRETE PRESSURE VESSELS	*Giacomo Torelli*, Martin Gillie, Parthasarathi Mandal, Van-Xuan Tran*	1038
9:15 - 9:30	OPTIMAL TUNING OF THERMOMECHANICAL HYBRID SIMULATION PARAMETERS	*Catherine Whyte*, Kevin Mackie, Giuseppe Abbiati, Bozidar Stojadinovic*	1055
9:30 - 10:00	**Coffee Break / Poster Session (Gallery Outside of McDonnell Hall A01/A02)**		
10:00 - 11:45	**Session 1-B.1: Concrete Columns & Walls (McDonnell Hall A02)** Co-Moderators: Kang Hai Tan & Faris Ali		**Proceedings Page**
10:00 - 10:15	PERFORMANCE COMPARISON BETWEEN RECTANGULAR AND CIRCULAR CROSS-SECTION COLUMNS IN FIRE SITUATION, USING TABULATED METHODS	*Maria Alzira Ramalho*, Miguel Gonçalves*	79
10:15 - 10:30	FIRE RESISTANCE OF REINFORCED CONCRETE COLUMNS SUBJECTED TO STANDARD FIRE - COMPARISON OF AN ADVANCED AND A SIMPLIFIED METHOD	*Marcus Achenbach*, Thomas Gernay, Guido Morgenthal*	86
10:30 - 10:45	BUCKLING STRENGTH OF SLENDER REINFORCED HSC AND VHSC COLUMNS IN FIRE	*Masaki Kato*, Shintaro Michikoshi, Shigeaki Baba, Kazumasa Imai*	94
10:45 - 11:00	EFFECTS OF LOCALISED OR NON-UNIFORM HEATING ON REINFORCED CONCRETE COLUMNS	*Jamie Maclean*, Vadims Goremikins, Luke Bisby, Tim Stratford*	102
11:00 - 11:15	MODELLING THE THERMAL AND STRUCTURAL PERFORMANCE OF A CONCRETE COLUMN EXPOSED TO A TRAVELLING FIRE - TISOVA FIRE TEST	*David Rush*, David Lange, Jamie Maclean, Egle Rackauskaite*	110

11:15 - 11:30	AN ANALYTICAL APPROACH FOR PREDICTING THE DEFORMED CONFIGURATION OF HIGH RISE CONCRETE WALLS SUBJECTED TO FIRE LOADING CONDITIONS	*Mingguan Yang, Samir Mehal, Duc Toan Pham*, Patrick de Buhan, Jean-Vivien Heck*	119
11:30 - 11:45	ON THE EFFECT OF DESIGN PARAMETERS AND BOUNDARY CONDITIONS ON THE POST-EARTHQUAKE FIRE PERFORMANCE OF RC STRUCTURAL WALLS	*Shuna Ni, Anna Birel**	135

10:00 - 11:45	**Session 1-B.2: Steel Connections and Floor Beams (McDonnell Hall A01)** Co-Moderators: Michael Engelhardt & Nicole Braxtan		**Proceedings Page**
10:00 - 10:15	CREEP BEHAVIOR OF FLUSH ENDPLATE CONNECTIONS AT ELEVATED TEMPERATURES DUE TO FIRE	*Ahmad El Ghor, Elie Hantouche, Mohammed Morovat*, Michael Engelhardt*	435
10:15 - 10:30	EXPERIMENTAL STUDY ON HIGH-STRENGTH BOLTS UNDER COMBINED TENSION AND SHEAR DURING AND AFTER FIRE	*Anne K. Kawohl*, Jörg Lange*	452
10:30 - 10:45	POST-FIRE MECHANICAL PROPERTIES OF GRADE 8.8 BOLTS	*Mahmood Yahyai*, Abbas Rezaeian, Alireza Poormohamadi, Mohamad Reza Eslami, Venkatesh Kodur*	460
10:45 - 11:00	THE EFFECTS OF LOAD INTENSITY AND RESTRAINT ON THE FIRE RESISTANCE OF STEEL AND COMPOSITE BEAMS	*Farid Alfawakhiri*, Charles Carter, Robert Berhinig, Patrick Zeeveld, Frederick Hervey*	484
11:00 - 11:15	EXPERIMENTAL AND NUMERICAL STUDY ON HIGH STRENGTH STEEL ENDPLATE CONNECTIONS AFTER FIRE	*Xuhong Qiang*, Xu Jiang, Frans Bijlaard, Henk Kolstein*	443
11:15 - 11:30	DEVELOPMENT AND MODIFICATION OF YIELD LINE PATTERNS IN THIN SLABS SUBJECTED TO TENSILE MEMBRANE ACTION	*Fabien Quichaud*, Ian Burgess, Shan-Shan Huang*	509
11:30 - 11:45	ADVANCED ANALYSIS OF THE MEMBRANE ACTION OF COMPOSITE SLABS UNDER NATURAL FIRE SCENARIOS: A CASE STUDY OF THE NEW JTI HEADQUARTERS	*Lorenzo Lelli*, Jonas Loutan*	517

11:45 - 13:00	**Lunch (Community Hall, Whitman College)**

13:00 - 14:45	**Session 1-C.1: Concrete Slabs & Beams (McDonnell Hall A02)** Co-Moderators: Pietro Gambarova & Anthony Abu		**Proceedings Page**
13:00 - 13:15	GLASS FIBRE REINFORCED POLYMER (GFRP) REINFORCED CONCRETE SLABS WITH LOW COVER IN FIRE	*Hamzeh Hajiloo*, Mark F. Green, Noureddine Bénichou, Mohamed Sultan*	3
13:15 - 13:30	THE EFFECT OF LITS ON PUNCHING SHEAR IN FIRE	*Rwayda Al Hamd*, Martin Gillie, Giacomo Torelli, Holly Smith, Tim Stratford, Yong Wang*	12
13:30 - 13:45	CONCRETE EDGE FAILURE OF HEADED STUD ANCHORS UNDER FIRE AND POST-FIRE CONDITIONS: VERIFICATION OF A 3D FE CODE	*Kaipei Tian*, Joško Ožbolt, Goran Periškic*	20
13:45 - 14:00	RATIONAL DESIGN APPROACH FOR PREDICTING FIRE RESISTANCE OF HOLLOWCORE SLABS	*Anuj Shakya*, Venkatesh Kodur*	28
14:00 - 14:15	SHEAR AND TORSION IN R/C STRUCTURAL MEMBERS IN FIRE	*Patrick Bamonte, Pietro Gambarova, Nataša Kalaba, Sergio Tattoni**	37
14:15 - 14:30	FIRE BEHAVIOR OF TWO-WAY POST-TENSIONED CONCRETE SLABS PROVIDED WITH BONDED TENDONS: AN EXPERIMENTAL STUDY	*Li Zhang*, Ya Wei, Francis Tat Kwong Au, Jing Li*	45
14:30 - 14:45	FIRE TEST OF FRP MEMBERS APPLIED TO RAILWAY BRIDGE	*Kamila Cabova*, Pavel Ryjacek, Ondrej Hrasky, Ludvik Kolpasky, Jan Vujtech, Frantisek Wald*	784

13:00 - 14:30	**Session 1-C.2: Metal Structures (McDonnell Hall A01)** Co-Moderators: František Wald & Kevin LaMalva		**Proceedings Page**
13:00 - 13:15	LATERAL-TORSIONAL BUCKLING OF BEAMS WITH CORRUGATED WEBS SUBJECTED TO FIRE	*Gonçalo Correia Lopes, Carlos Couto, Paulo Vila Real*, Nuno Lopes*	**360**
13:15 - 13:30	FIRE-INDUCED PROGRESSIVE COLLAPSE OF 3D STEEL FRAMES WITH CONCRETE FLOORS	*Jian Jiang*, Guo-Qiang Li*	**368**
13:30 - 13:45	EVALUATING POST-FIRE MECHANICAL BEHAVIOR OF ULTRA-HIGH STRENGTH (GRADE1200) STEEL TUBES	*Fatemeh Azhari*, Amin Heidarpour, Xiao-Ling Zhao, Christopher Hutchinson*	**377**
13:45 - 14:00	EXPERIMENTAL AND NUMERICAL ANALYSIS OF COLD-FORMED STEEL COLUMNS AT BOTH AMBIENT TEMPERATURE AND SIMULATED FIRE CONDITIONS	*Hélder D. Craveiro, João Paulo C. Rodrigues, Luís Laím**	**408**
14:00 - 14:15	MODELING FIRE INDUCED BURNTHROUGH RUPTURE OF MARINE GRADE ALUMINUM PANELS	*Christian Rippe*, Scott Case, Brian Lattimer*	**417**
14:15 - 14:30	BUCKLING ANALYSIS OF RACK UPRIGHTS EXPOSED TO LOCALISED FIRES	*Shubin He, Chong Ren*, Xianzhong Zhao, Chunxiang Li*	**425**
14:45 - 15:15	**Coffee Break / Poster Session (Gallery Outside of McDonnell Hall A01/A02)**		
15:15 - 16:45	**Session 1-D.1: Timber (McDonnell Hall A02)** Co-Moderators: Andrea Frangi & Andy Buchanan		**Proceedings Page**
15:15 - 15:30	DEVELOPMENT OF WOOD STRUCTURAL ELEMENTS FOR FIRE RESISTANT BUILDINGS	*Hirokazu Ohashi*, Shinya Igarashi, Tsutomu Nagaoka*	**635**
15:30 - 15:45	CHANGING FAILURE MODES OF CROSS-LAMINATED TIMBER	*Richard Emberley*, Alexander Nicolaidis, Dilum Fernando, José L. Torero*	**643**
15:45 - 16:00	PARAMETERS INFLUENCING THE BEHAVIOUR OF TIMBER FRAME ASSEMBLIES EXPOSED TO FIRE, DEVELOPMENT OF NEW DESIGN CRITERIA FOR INSULATION MATERIALS	*Mattia Tiso*, Alar Just*	**659**
16:00 - 16:15	SECTIONAL ANALYSIS OF CROSS-LAMINATED TIMBER BEAMS AS A DESIGN FOR FIRE METHODOLOGY	*Alastair Bartlett*, Rory Hadden, Luke Bisby, Barbara Lane*	**684**
16:15 - 16:30	TIMBER UNDER REAL FIRE CONDITIONS - THE INFLUENCE OF OXYGEN CONTENT AND GAS VELOCITY ON THE CHARRING BEHAVIOR	*Joachim Schmid*, Daniel Brandon, Alessandro Santomaso, Ulf Wickström, Andrea Frangi*	**692**
16:30 - 16:45	FULL-SCALE FIRE TEST OF A LATERALLY LOADED LIGHT TIMBER-FRAMED COMPARTMENT	*Daniel Jessop, Anthony Abu*, Colleen Wade, Michael Spearpoint, Hans Gerlich, Andy Buchanan*	**700**
15:15 - 16:45	**Session 1-D.2: Numerical Modeling (McDonnell Hall A01)** Co-Moderators: Angus Law & Ann Jeffers		**Proceedings Page**
15:15 - 15:30	CONSTITUTIVE MODELLING OF DUCTILE METALS AT HIGH TEMPERATURE	*Pawel Woelke*, Ryan Anderson, Badri Hiriyur, Najib Abboud*	**604**
15:30 - 15:45	FDS-FEM SIMULATION METHOD AND ITS APPLICATION TO MODEL LOCALIZED FIRE TESTS ON STEEL MEMBERS	*Chao Zhan**	**992**
15:45 - 16:00	SCALING OF REACTION FORCES IN A DISPLACEMENT CONTROLLED STEEL BEAM, TRANSITIONING FROM ELASTIC TO PLASTIC BEHAVIOUR	*Kim Olsson*, David Lange, Lars Boström*	**1016**
16:00 - 16:15	FACTORS GOVERNING THE FIRE RESPONSE OF REACTIVE POWDER CONCRETE SIMPLY-SUPPORTED BEAMS	*Xiaomeng Hou*, Pengfei Ren, Wenzhong Zheng, Qin Rong, Yao Zhan*	**1024**

Time	Title	Authors	Proceedings Page
16:15 - 16:30	NUMERICAL ANALYSES FOR PRECAST RC STRUCTURES AT FIRE CONDITION IN UNDERGROUND SPACE	*K.H. Tan*, J.X. Liu*	1032
16:30 - 16:45	MODELLING OF BOND-SLIP BETWEEN PRESTRESSED STRANDS AND CONCRETE AT ELEVATED TEMPERATURES	*Jamal Khalaf, Zhaohui Huang**	71
18:00 - 20:00	**Reception (*Chancellor Green Rotunda*)**	***Co-sponsored by American Institute of Steel Construction (AISC) and Underwriters Laboratories (UL)***	

Thursday June 9, 2016

Time	Title	Authors	Proceedings Page
7:00 - 8:00	**Registration and Continental Breakfast (Gallery Outside of McDonnell Hall A01/A02)**		
8:00 - 9:15	**Session 2-A: Concrete Slabs & Beams (McDonnell Hall A02)** Co-Moderators: Venkatesh Kodur & Mark Green		**Proceedings Page**
8:00 - 8:15	INSIGHTS INTO THE COMPLEXITY OF STRUCTURAL FIRE RESPONSE FROM REPEATED HEATING TESTS ON POST-TENSIONED CONCRETE	*John Gales*, Luke Bisby*	53
8:15 - 8:30	QUANTIFYING THE EFFECT OF TEMPERATURE INDUCED BOND DEGRADATION ON FIRE RESISTANCE OF RC BEAMS	*Ankit Agrawal*, Venkatesh Kodur*	62
8:30 - 8:45	EFFECT OF BIAXIAL MECHANICAL LOADING AND CEMENT TYPE ON FIRE SPALLING BEHAVIOUR OF CONCRETE	*Md Jihad Miah, Francesco Lo Monte*, Pierre Pimienta, Roberto Felicetti*	233
8:45 - 9:00	PULSE-ECHO MONITORING OF CONCRETE DAMAGE AND SPALLING DURING FIRE TESTS	*Roberto Felicetti*, Francesco Lo Monte*	851
9:00 - 9:15	INTENSITY MEASURES FOR PROBABILISTIC STRUCTURAL FIRE ENGINEERING	*Peter Moss, Anthony Abu*, Rajesh Dhakal*	933
9:15 - 9:30	**1-minute Oral "Commercials" of Posters (PechaKucha Style) (McDonnell Hall A02)** Moderator: Maria Garlock		
9:30 - 10:00	**Coffee Break/Poster Session (Gallery Outside of McDonnell Hall A01/A02)**		
10:00 - 11:45	**Session 2-B.1: Concrete Spalling (McDonnell Hall A02)** Co-Moderators: Luc Taerwe & Roberto Felicetti		**Proceedings Page**
10:00 - 10:15	THERMAL BOUNDARY CONDITIONS WHEN FIRE TESTING CONCRETE	*Cristian Maluk, Angus Law, Jose Luis Torero**	209
10:15 - 10:30	PREDICTIVE TESTING FOR HEAT INDUCED SPALLING OF CONCRETE TUNNELS - THE INFLUENCE OF MECHANICAL LOADING	*Ieuan Rickard*, Luke Bisby, Susan Deeny, Cristian Maluk*	217
10:30 - 10:45	EXPLOSIVE CONCRETE SPALLING DURING LARGE-SCALE FIRE RESISTANCE TESTS	*Cristian Maluk*, Luke Bisby, Giovanni P. Terrasi*	225
10:45 - 11:00	EFFECTS OF POLYPROPYLENE FIBERS ON PREVENTING CONCRETE SPALLING IN FIRE	*Fangxia Lu, Mario Fontana**	241
11:00 - 11:15	REUSE OF WASTE TYRE FIBRES IN CONCRETE - FIRE-SPALLING MITIGATION	*Shun Hey Dawn Hou, Shan-Shan Huang*, Harris Angelakopoulos, Kypros Pilakoutas, Ian Burgess*	249
11:15 - 11:30	BEHAVIOR OF STRUCTURAL TUNNEL ELEMENTS EXPOSED TO FIRE AND MECHANICAL LOADING	*Matthias Siemon*, Jochen Zehfuß*	791

11:30 - 11:45	EXPERIMENTAL STUDY ON MECHANICAL PROPERTIES OF ULTRA-HIGH STRENGTH CONCRETE AT ELEVATED TEMPERATURES	*Mingxiang Xiong, J.Y. Richard Liew, Yong Du**	273
10:00 - 11:45	**Session 2-B.2: Bridges (McDonnell Hall A01)** Co-Moderators: Kevin Mueller & Nestor Iwankiw		**Proceedings Page**
10:00 - 10:15	FACTORS GOVERNING RESPONSE OF STEEL BRIDGE GIRDERS UNDER FIRE CONDITIONS	*Esam Aziz*, Venkatesh Kodur*	727
10:15 - 10:30	POSTBUCKLING SHEAR STRENGTH AT ELEVATED TEMPERATURES USING A DIAGONAL COMPRESSION MODEL	*Jonathan Glassman*, Maria Garlock*	735
10:30 - 10:45	ANALYSIS OF THE FACTORS THAT INFLUENCE THE MAXIMUM ADIABATIC TEMPERATURES IN I-GIRDER BRIDGES DURING FIRE EVENTS	*Guillem Peris-Sayol, Ignacio Paya-Zaforteza*, Sebastià Balasch-Parisi, José Alós-Moya*	743
10:45 - 11:00	RESILIENT BRIDGE DESIGN FRAMEWORK TO EXTREME FIRE LOADING	*Kevin Mueller*, Shalva Marjanishvili, Spencer Quiel*	751
11:00 - 11:15	ASSESSING THE FIRES ON THE DECK OF CABLE STAYED BRIDGES	*Panagiotis Kotsovinos*, Gary Walker, Graeme Flint, Barbara Lane*	759
11:15 - 11:30	NEW DESIGN FIRES FOR PERFORMANCE BASED ENGINEERING OF HIGHWAY BRIDGES	*Jiayu Hu*, Ricky Carvel, Abdel Sanad, Asif Usmani*	768
11:30 - 11:45	PERFORMANCE-BASED PRIORITIZATION OF FIRE MITIGATION FOR HIGHWAY BRIDGES	*Spencer Quiel*, Zheda Zhu, Kevin Mueller, Aerik Carlton, Shalva Marjanishvili*	776
11:45 - 13:00	**Lunch (Community Hall, Whitman College)**		
13:00 - 14:45	**Session 2-C.1: Concrete Material Characterization (McDonnell Hall A02)** Co-Moderators: Emidio Nigro & Markus Knobloch		**Proceedings Page**
13:00 - 13:15	CONSTITUTIVE MODELS OF CONCRETE AT ELEVATED TEMPERATURES: STUDYING THE EFFECT OF TEMPERATURE GRADIENTS	*Quang Xuan Le, Vinh The Ngoc Dao*, Cristian Maluk, Luke Bisby, José Luis Torero*	257
13:15 - 13:30	POST-COOLING STRESS-STRAIN MODEL OF TRADITIONAL AND HIGH STRENGTH CONCRETE	*Emmanuel Annerel, Tom Van Den Steen, Luc Taerwe**	265
13:30 - 13:45	ASSESSING TENSILE PROPERTIES OF FIRE-DAMAGED ENGINEERED CEMENTITIOUS COMPOSITE WITH HYBRID FIBRES	*Jin-Cheng Liu*, Kang Hai Tan*	282
13:45 - 14:00	EXPERIMENTAL VALIDATION OF THE DAMAGE-PLASTICITY MODELINGCONCEPT FOR NORMAL STRENGTH CONCRETE IN FIRE	*Martin Neuenschwander*, Claudio Scandella, Markus Knobloch, Mario Fontana*	293
14:00 - 14:15	THERMAL PROPERTIES OF GREEN HIGH-PERFORMANCE FIBER-REINFORCED CEMENTITIOUS COMPOSITES SUBJECTED TO HIGH TEMPERATURE	*Xiuling Li*, Huining Zhang, Genda Chen, Yi Bao*	309
14:15 - 14:30	INFLUENCE OF WATER ON LOAD INDUCED THERMAL STRAIN OF CONCRETE	*Heisuke Yamashita*, Toru Yoshida, Takeo Hirashima*	316
14:30 - 14:45	ELEVATED TEMPERATURE BEHAVIOR OF IMPACT-INDUCED PARTIALLY DAMAGED CONCRETE	*Mahsa Mirmomeni, Amin Heidarpour*, Xiao-Ling Zhao, Jeffrey A. Packer*	324
13:00 - 14:45	**Session 2-C.2: Experimental Methods + Traveling Fires (McDonnell Hall A01)** Co-Moderators: John Gross & Florian Block		**Proceedings Page**
13:00 - 13:15	TEMPERATURE AND STRAIN MEASUREMENTS WITH FIBER OPTIC SENSORS FOR STEEL BEAMS SUBJECTED TO FIRE	*Yi Bao, Yizheng Chen, Mathhew Hoehler, Christopher Smith, Matthew Bundy, Genda Chen**	803
13:15 - 13:30	CONSOLIDATED FIRE TESTING - COUPLED THERMO-MECHANICAL MODELLING FOR GLOBAL STRUCTURAL FIRE ANALYSIS	*Patrick Schulthess*, Martin Neuenschwander, Markus Knobloch, Mario Fontana*	819

13:30 - 13:45	A STATIC PARTITIONED SOLVER FOR HYBRID FIRE TESTING	*Nicola Tondini*, Giuseppe Abbiati, Luca Possidente, Bozidar Stojadinovic*	827
13:45 - 14:00	STABILITY IN HYBRID FIRE TESTING	*Ana Sauca*, Thomas Gernay, Fabienne Robert, Nicola Tondini, Jean Marc Franssen*	836
14:00 - 14:15	IMPLEMENTATION OF A NEW DESIGN TRAVELLING FIRE MODEL FOR GLOBAL STRUCTURAL ANALYSIS	*Xu Dai*, Liming Jiang, Jamie Maclean, Stephen Welch, Asif Usmani*	959
14:15 - 14:30	GLOBAL STRUCTURAL BEHAVIOR OF STEEL-CONCRETE COMPOSITE FLOOR SYSTEMS UNDER TRAVELING FIRES	*Jason Martinez*, Ann E. Jeffers*	967
14:30 - 14:45	STRUCTURAL RESPONSE OF A GENERIC STEEL FRAME EXPOSED TO TRAVELLING FIRES	*Egle Rackauskaite*, Panagiotis Kotsovinos, Ann Jeffers, Guillermo Rein*	975
14:45 - 15:15	**Coffee Break/Poster Session (Gallery Outside of McDonnell Hall A01/A02)**		

15:15 - 17:00	**Session 2-D.1: Fiber Reinforcement and Strengthening (McDonnell Hall A02)** Co-Moderators: Thomas Gernay & Olivier Vassart		**Proceedings Page**
15:15 - 15:30	EFFECTS OF POLYPROPYLENE AND STEEL FIBERS ON PERMEABILITY OF ULTRA-HIGH PERFORMANCE CONCRETE AT HOT STATE	*Y. Li*, K.H. Tan*	145
15:30 - 15:45	NUMERICAL STUDY ON STEEL FIBER REINFORCED CONCRETE COLUMNS SUBJECTED TO FIRE	*Venkatesh Kodur, Pratik Bhatt*, Vasant Matsagar*	153
15:45 - 16:00	EXPERIMENTAL STUDY OF ULTRA-HIGH PERFORMANCE FIBRE REINFORCED CONCRETE UNDER ISO 834 FIRE	*Charles Kahanji, Faris Ali*, Ali Nadjai*	165
16:00 - 16:15	FIRE TESTS ON FIBER SHEET STRENGTHENED RC BEAMS USING GEOPOLYMERS AS ADHESIVE AGENT	*Hai Yan Zhang*, Qi Shu Liang, Venkatesh Kodur, Hao Ran Lv*	174
16:15 - 16:30	ELEVATED TEMPERATURE RESPONSE OF RC BEAMS STRENGTHENED WITH NSM FRP BARS BONDED WITH CEMENTITIOUS GROUT	*Iolanda Del Prete*, Antonio Bilotta, Luke Bisby, Emidio Nigro*	181
16:30 - 16:45	FLEXURAL CAPACITY OF NSM FRP STRENGTHENED RC BEAMS AT ELEVATED TEMPERATURE	*Iolanda Del Prete, Antonio Bilotta, Daniele Di Fiore, Emidio Nigro**	190
16:45 - 17:00	FIRE TESTING OF INSULATED RC BEAMS STRENGTHENED WITH NEAR SURFACE MOUNTED FRP REINFORCEMENT	*Alessandro Proia, Stijn Matthys, Luc Taerwe*, Aniello Palmieri*	199

15:15 - 17:00	**Session 2-D.2: Fire Protection Materials (McDonnell Hall A01)** Co-Moderators: Catherine Whyte & Mahmood Tabaddor		**Proceedings Page**
15:15 - 15:30	EXPERIMENTAL STUDY OF THE BEHAVIOUR OF STEEL STRUCTURES PROTECTED BY DIFFERENT INTUMESCENT COATINGS AND EXPOSED TO VARIOUS FIRE SCENARIOS	*Andrea Lucherini*, Razvan-Ioan Costa, Luisa Giuliani, Grunde Jomaas*	1065
15:30 - 15:45	AN IMPROVED METHOD FOR THERMAL ANALYSIS OF INTUMESCENT COATINGS	*Anita Treven*, Tomaž Hozjan, Miran Saje*	1073
15:45 - 16:00	EXPERIMENTAL TESTS ON INTUMESCENT COATING FOR PROTECTING STEEL STRUCTURES	*Donatella de Silva*, Antonio Bilotta, Emidio Nigro*	1081
16:00 - 16:15	AN EXPERIMENTAL STUDY OF THE DAMAGE MODES OF FIREPROOF COATINGS UNDER COMPLEX LOADS	*Suwen Chen*, Yan-Jun Wang, Liming Jiang, Asif Usmani*	1090
16:15 - 16:30	FIRE TESTS OF REACTIVE FIRE PROTECTION SYSTEMS APPLIED TO STEEL TENSION MEMBERS WITH SOLID CIRCULAR SECTION	*Dustin Häßler*, Sascha Hothan*	1099

16:30 - 16:45	NUMERICAL INVESTIGATION OF PLASTERBOARD PARTITIONS SUBJECTED TO FIRE: CONFRONTATION BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS	*Guillaume Cueff*, Gildas Auguin*	1107
16:45 - 17:00	MATERIAL CHARACTERISATION AND NUMERICAL MODELLING OF GYPSUM PLASTERBOARDS IN FIRE	*Maneesha Dodangoda*, Mahen Mahendran, Keerthan Poologanathan, Ray Frost*	1116
19:00 - 22:00	**Dinner (*Prospect House*)**		

	Friday, June 10, 2016		
7:00 - 8:00	**Continental Breakfast (Gallery Outside of McDonnell Hall A01/A02)**		
8:00 - 9:15	**Session 3-A: Timber (McDonnell Hall A02)** Co-Moderators: Mario Fontana & Joachim Schmid		**Proceedings Page**
8:00 - 8:15	EXTERNAL AN INTERNAL FACTORS INFLUENCING THE CHARRING OF TIMBER – AN EXPERIMENTAL STUDY WITH RESPECT TO NATURAL FIRES AND MOISTURE CONDITIONS	*Norman Werther**	650
8:15 - 8:30	DEFLECTION BEHAVIOR AND LOAD-BEARING-PERIOD OF STRUCTURAL GLUED LAMINATED TIMBER BEAMS IN FIRE INCLUDING COOLING PHASE	*Yusuke Katakura*, Hitoshi Kinjo, Takeo Hirashima, Shuitsu Yusa, Kiyoshi Saito*	667
8:30 - 8:45	SIMULATION OF CHARRING DEPTH OF WOODEN-BASED PRODUCTS WHEN EXPOSED TO NON-STANDARDIZED FIRE CURVES	*Jean-Christophe Mindeguia*, Guillaume Cueff, Virginie Dréan, Gildas Auguin*	675
8:45 - 9:00	A FRAMEWORK FOR FINITE ELEMENT MODELLING OF TIMBER CONNECTIONS IN FIRE	*Pedro Palma*, Andrea Frangi*	708
9:00 - 9:15	PERFORMANCE OF GYPSUM-PROTECTED CLT AND NLT IN NATURAL AND STANDARD FIRES	*Marc Janssens*, Jason Huczek, Natasha Albracht*	1124
9:15 - 9:45	**Coffee Break / Poster Session (Gallery Outside of McDonnell Hall A01/A02)**		
9:45 - 11:00	**Session 3-B.1: Applications of Fire Safety (McDonnell Hall A02)** Co-Moderators: Jonathan Glassman & Marc Janssens		**Proceedings Page**
9:45 - 10:00	TOWARDS A STANDARD MEASURE OF THE ABILITY OF A STRUCTURE TO RESIST A NATURAL FIRE	*Thomas Gernay, Jean-Marc Franssen**	861
10:00 - 10:15	EVALUATION OF COMPOSITE STEEL-CONCRETE SLAB PERFORMANCE SUBJECTED TO TRAVELLING FIRE: A CASE STUDY	*Bernice V. Y. Wong*, Rui R. Sun*	501
10:15 - 10:30	PERFORMANCE-BASED FIRE ENGINEERING: SENSITIVITY ANALYSIS ON DESIGN PARAMETERS	*Reza Imani*, Pierre Ghisbain, Ali Ashrafi*	877
10:30 - 10:45	SHEAR BREAKING OF COLUMNS SUBJECTED TO LOCALIZED FIRE	*Olivier Burnier**	885
10:45 - 11:00	CONVERSION OF VISUAL POST FIRE MEASUREMENTS INTO FIRE SEVERITY WITH THE AID OF THERMO-PLASTIC ANALYSIS FOR RETROFITTING	*Tom Molkens*, Thomas Gernay, Ruben Van Coile*	893

Time	Title	Authors	Proceedings Page
9:45 - 11:00	**Session 3-B.2: Composite Columns (McDonnell Hall A01)** Co-Moderators: Guo-Qiang Li & Peter Schaumann		**Proceedings Page**
9:45 - 10:00	STABILITY BEHAVIOR OF CONCRETE-FILLED STEEL TUBE COLUMNS IN REAL FIRE CONDITIONS	*Shashank Taddhanpally, Anil Agarwal**	527
10:00 - 10:15	NUMERICAL ANALYSIS OF THE FIRE PERFORMANCE OF INNOVATIVE STEEL-CONCRETE COMPOSITE COLUMNS.	*Ana Espinós, Manuel L. Romero*, Dennis Lam*	552
10:15 - 10:30	EXPERIMENTAL INVESTIGATION ON AXIALLY AND ROTATIONALLY RESTRAINED CIRCULAR AND ELLIPTICAL CONCRETE-FILLED HOLLOW COLUMNS SUBJECTED TO FIRE	*João P C Rodrigues*, Luís Laím*	560
10:30 - 10:45	FLEXURAL BEHAVIOURS OF REINFORCED CONCRETE COLUMNS CONFINED BY CIRCULAR STEEL TUBES AFTER FIRE EXPOSURE	*Faqi Liu*, Hua Yang, Sumei Zhang*	568
10:45 - 11:00	EXPERIMENTAL STUDY ON BOND-SLIP BETWEEN SHAPED STEEL AND CONCRETE UNDER HIGH TEMPERATURE	*Yuzhuo Wang*, Dejian Xu, Chunyang Liu, Chuanguo Fu*	576
11:00 - 11:30	**Coffee Break / Poster Session (Gallery Outside of McDonnell Hall A01/A02)**		
11:30 - 12:30	**Session 3-B.3: Probabilistic Approaches (McDonnell Hall A02)** Co-Moderators: Ignacio Paya-Zaforteza & John Gales		**Proceedings Page**
11:30 - 11:45	ENGINEERING AN ICON OR THE PROBABILISTIC-BASED STRUCTURAL FIRE ENGINEERING OF THE BATTERSEA POWER STATION	*Florian M. Block*, Tad-Song Kho*	901
11:45 - 12:00	FIRE FRAGILITY FUNCTIONS FOR COMMUNITY RESILIENCE ASSESSMENT	*Negar Elhami Khorasani*, Thomas Gernay, Maria Garlock*	909
12:00 - 12:15	CRITICAL PARAMETERS IN DERIVING FIRE FRAGILITY FUNCTIONS FOR STEEL GRAVITY FRAMES	*Thomas Gernay*, Negar Elhami Khorasani, Maria Garlock*	917
12:15 - 12:30	APPLYING UNCERTAINTY QUANTIFICATION IN MODELLING OF A STEEL BEAM EXPOSED TO FIRE	*Johan Anderson*, David Lange, Lars Bostrom*	925
11:30 - 12:30	**Session 3-B.4:Steel Material Characterization (McDonnell Hall A01)** Co-Moderators: Ian Burgess & Spencer Quiel		**Proceedings Page**
11:30 - 11:45	S500M AND GRADE 70 STEEL GRADES - MATERIAL PROPERTIES ASSESSEDTHROUGH FULL SCALE TESTS	*François Hanus, Olivier Vassart*, Nicolas Caillet, Jean-Marc Franssen*	589
11:45 - 12:00	DEVELOPMENT OF TRUE STRESS-STRAIN CURVES OF STRUCTURE STEEL FOR FRACTURE SIMULATIONS	*Michael D. Engelhardt*, Wenyu Cai*	597
12:00 - 12:15	BEHAVIOUR OF HIGH STRENGTH STEEL UNDER FIRE CONDITIONS	*Dorothy Winful*, Katherine A Cashell, Adrienne M Barnes, Richard J Pargeter*	624
12:15 - 12:30	A UNIFIED RHEOLOGICAL MODEL FOR ANALYSIS OF STEEL BEHAVIOUR AT HIGH TEMPERATURE	*Neno Toric*, Ian W. Burgess, Josip Brnic, Ivica Boko, Goran Turkalj, Marko Canadija, Alen Harapin, Vladimir Divic, Ivana Uzelac*	1008
12:30 - 13:45	**Lunch (Community Hall, Whitman College)**		

Time	Session 3-C: Steel Structures (McDonnell Hall A02) Co-Moderators: Paulo Vila-Real & Negar Elhami Khorasani		Proceedings Page
13:45 - 15:15			
13:45 - 14:00	TEMPERATURE ASSESSMENT OF A VERTICAL STEEL MEMBER SUBJECTED TO LOCALISED FIRE : EXPERIMENTAL TESTS	*François Hanus*, Olivier Vassart, Nicola Tondini, Ali Nadjai, Jean-Marc Franssen*	**343**
14:00 - 14:15	COMPONENT-BASED ELEMENT OF BEAM LOCAL BUCKLING ADJACENT TO CONNECTIONS IN FIRE	*Guan Quan*, Shan-Shan Huang, Ian Burgess*	**352**
14:15 - 14:30	THE PERFORMANCE OF STRUCTURAL STEEL BEAMS SUBJECT TO A LOCALIZED FIRE	*Lisa Choe*, Selvarajah Ramesh, Chao Zhang, John Gross*	**392**
14:30 - 14:45	DEVELOPMENT OF A CALCULATION METHOD FOR THE FIRE DESIGN OF CONCRETE-FILLED STEEL TUBULAR COLUMNS	*Ana Espinós*, Manuel L. Romero, Vicente Albero, Antonio Hospitaler, Gisèle Bihina, Christophe Renaud*	**535**
14:45 - 15:00	EXPERIMENTAL AND NUMERICAL INVESTIGATIONS ON THE COMPOSITE BEHAVIOR OF CONCRETE-FILLED TUBULAR COLUMNS WITH MASSIVE STEEL CORE AT HIGH TEMPERATURES	*Peter Schaumann, Inka Kleiboemer**	**544**
15:00 - 15:15	COMPARATIVE BEHAVIOR OF FIRE-EXPOSED COMPOSITE GIRDERS SUBJECTED TO FLEXURAL AND SHEAR LOADING	*Mohannad Naser*, Venkatesh Kodur*	**719**
15:45 - 16:30	**Closing Ceremony (McDonnell Hall A02)**		

POSTERS		Proceedings Page
A THERMO MECHANICAL EXPERIMENTAL INVESTIGATION ON 3 LOADED CONCRETE WALLS EXPOSED TO ISO 834-1 FIRE	*Nicolas Pinoteau, Md Jihad Miah, Pierre Pimienta*	**127**
POST-FIRE RESIDUAL MECHANICAL PROPERTIES OF HIGH STRENGTH CONCRETE (HSC) MADE WITH BASALT AGGREGATE	*Marcela Sollero, Armando Moreno Júnior*	**301**
3D FEA OF LOAD-BEARING COLD-FORMED STEEL WALL SYSTEMS WITH WEB-PERFORATED STUDS SUBJECTED TO STANDARD FIRE	*Shijun Yang, Lei Xu*	**400**
EFFECT OF INITIAL GEOMETRICAL IMPERFECTION ON THE PERFORMANCE OF SINGLE-LAYER RETICULATED SHELLS AT ELEVATED TEMPERATURES	*Ye-Hua Wang, Zu-Yan SHen, Yuan-Qi Li*	**385**
ANALYTICAL STUDY ON CRITICAL TEMPERATURE OF BOLTED SPLICE CONNECTIONS	*Robert Dwiputra, Shuhei Ando, Takeo Hirashima*	**468**
FIRE PERFORMANCE OF HYBRID STAINLESS-CARBON STEEL COMPOSITE BEAM-COLUMN JOINTS WITH BLIND-BOLTED CONNECTIONS	*Tian-Yi Song, Zhong Tao, Ali Razzazzadeh, Lin-Hai Han*	**476**
NUMERICAL MODELING OF HEAT TRANSFER IN STEEL-CONCRETE COMPOSITE SLABS	*Jian Jiang, Joseph Main, Jonathan Weigand, Fahim Sadek*	**492**
HIGH-TEMPERATURE MATERIAL CONSTITUTIVE MODELS FOR STRUCTURAL-FIRE ANALYSIS	*Chao Zhang, Lisa Choe, John Gross*	**616**
THERMOGRAPHIC DIGITAL IMAGE CORRELATION (TDIC) MEASUREMENTS OF MECHANICALLY-LOADED STRUCTURES WITH FIRE IN THE FIELD OF VIEW	*Jonathan Hodges, Christian Rippe, Scott Case, Brian Lattimer*	**811**
ASSESSMENT OF CONCRETE EXPOSED TO ELEVATED TEMPERATURES USING SCANNING ELECTRON MICROSCOPY AND X-RAY DIFFRACTION	*Bruno Fernandes, Fabrício Bolina, Augusto Gil, Eduardo Estevam, Bernardo Tutikian*	**844**
APPLICATION OF CONCEPTS OF FIRE RESISTANCE OF LOAD BEARING STRUCTURAL GLASS	*Johan Sjöström, David Lange, Michaël Debuyser, Daniel Honfi, Delphine Sonck, Jan Belis*	**869**
A PROBABILISTIC STUDY ON CONCRETE COLUMNS EXPOSED TO BIAXIAL BENDING AT ELEVATED TEMPERATURES	*Lijie Wang, Ruben Van Coile, Robby Caspeele, Luc Taerwe*	**942**
RELIABILITY OF REINFORCED CONCRETE WALLS SUBJECTED TO STANDARD FIRE USING ADVANCED AND SIMPLIFIED METHODS	*Marcus Achenbach, Guido Morgenthal*	**949**
NUMERICAL CALIBRATION OF HYDROCARBON LOCALISED FIRE TESTS BY MEANS OF FIRE DYNAMICS SIMULATOR	*Nicola Tondini, Christophe Thauvoye, François Hanus, Bin Zhao*	**983**
STRUCTURAL BEHAVIOUOR UNDER LOCALISED FIRE ACTION-MODELLED USING AN INTEGRATED COMPUTATIONAL TOOL	*Liming Jiang, Suwen Chen, Asif Usmani*	**1047**
NUMERICAL ANALYSIS OF FRP REINFORCED BRIDGE COMPONENTS IN FIRE	*Hamzeh Hajiloo, Mark F. Green*	

附錄二

研討會論文摘錄

1

混凝土材料性質

1. Experimental Validation of the Damage-Plasticity Modeling Concept for Normal Strength Concrete in Fire
2. Effect of Biaxial Mechanical Loading and Cement Type on the Fire Spalling Behaviour of Concrete
3. Thermal Properties of Green High-Performance Fiber-Reinforced Cementitious Composites Subjected to High Temperature
4. Experimental Study on Mechanical Properties of Ultra-high Strength Concrete at Elevated Temperatures
5. Post-Fire Residual Mechanical Properties of High Strength Concrete (HSC) Made with Basalt Aggregate
6. Effects of Polypropylene and Steel Fibers on Permeability of Ultra-high Performance Concrete at Hot State

Experimental Validation of the Damage-Plasticity Modeling Concept for Normal Strength Concrete in Fire

MARTIN NEUENSCHWANDER[1], CLAUDIO SCANDELLA[1], MARKUS KNOBLOCH[2] and MARIO FONTANA[1]

ABSTRACT

The softening behavior of concrete and its elastic stiffness evolution with increasing plastic straining can be investigated experimentally with strain-rate controlled uniaxial cyclic compression tests. Such tests at ambient temperature show that concrete exhibits the phenomenon of elastic stiffness degradation, which can be captured by damage-plasticity models. However, temperature-dependent concrete models implementing this modeling concept are often used today in structural fire engineering, despite the lack of experiment-based validation data. This paper presents the results of a preliminary study on the behavior of normal strength concrete under cyclic compressive loading at elevated temperatures. The experimentally derived evolutions of the elastic stiffness with plastic strain confirm (1) the suitability of the damage-plasticity modeling concept for concrete in compression at elevated temperatures and (2) provide novel calibration data.

INTRODUCTION

Failure analysis of concrete and composite structures in fire that accounts for effects due to load-redistributions and confinement action, is an important task in structural fire engineering. In this framework, advanced generic concrete models, capable of considering these effects have become an important tool for analysis since they are available as temperature-dependent constitutive material models in some finite-element method software packages. However, these models were developed only on the basis of phenomena, observed in the concrete's macroscopic behavior in fracture experiments at ambient temperature.

Plasticity-based concrete models can capture the main macroscopic characteristic of the softening behavior of concrete that consists of a decreasing yield stress upon loading, which is accompanied by irreversible (plastic) strains and inelastic volumetric expansion (depending on the confining pressure). However, plasticity models alone cannot account for the stiffness degradation that has been

[1] ETH Zurich, Department of Civil and Environmental Engineering, Institute of Structural Engineering – Steel, Timber and Composite Structures, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland.

[2] Ruhr Universität Bochum, Department of Civil and Environmental Engineering, Institute of Steel, Lightweight and Composite Structures, Universitätsstraße 150, 44801 Bochum, Germany.

Effect of Biaxial Mechanical Loading and Cement Type on the Fire Spalling Behaviour of Concrete

MD JIHAD MIAH, FRANCESCO LO MONTE, PIERRE PIMIENTA and ROBERTO FELICETTI

ABSTRACT

Fire spalling of concrete is a complex phenomenon, which might occur due to pressure build-up in the pores, thermal- and load-induced stresses. In this context, eight mid-size ordinary concrete slabs (4of B40-II and 4 of B40-III concrete: fc28 ≈ 40 MPa) were heated at the bottom face according to Standard Fire curve (ISO 834-1), while a constant biaxial compressive load was applied. Four different levels of biaxial mechanical loading have been investigated on both concretes. The test results showed that the loaded specimens are more prone to spalling than unloaded specimens, with increasing amount of spalling for higher values of applied load. Concrete made with CEM III cement (B40-III: 43 % of slag) exhibited less spalling than CEM II cement concrete (B40-II: 3 % of slag).

INTRODUCTION

Thermal spalling is a sudden and violent breaking away of a surface layer of heated concrete. Fire spalling reduces the cross-sectional area and may lead to the direct exposure of rebars to flame, with a significant reduction of the load bearing capacity [1-2]. Two physical mechanisms are often associated with this phenomenon, namely: the build-up of pore pressure and thermal stresses in the concrete when exposed to a rapidly increasing temperature [1-2]. Despite a large body of literature, controversial opinions exist about the causes of spalling. It is worth noting, however, that a huge number of experimental studies have been reported in the literature on unloaded specimens [1-3], while very limited experimental studies are available on the fire spalling behaviour of concrete under mechanical loading condition [4-9].

Kodur et al. 2007 [4] and Boström et al. 2007 [5] concluded that the type of loading and its intensity have significant influence on fire spalling behaviour

Md Jihad Miah [1], Francesco Lo Monte [2], Pierre Pimienta [1] and Roberto Felicetti [2]
[1]Université Paris Est, Centre Scientifique et Technique du Bâtiment (CSTB), France
[2] Department of Civil and Environmental Engineering, Politecnico di Milano, Milan, Italy
Jihad.miah@cstb.fr,francesco.lo@polimi.it, pierre.pimienta@cstb.fr, roberto.felicetti@polimi.it

of concrete.

Thermal Properties of Green High-Performance Fiber-Reinforced Cementitious Composites Subjected to High Temperature

XIULING LI, HUINING ZHANG, GENDA CHEN and YI BAO

ABSTRACT

To study the influences of mix proportions and high temperature on the thermal properties of green high-performance fiber reinforced cementitious composites (GHPFRCC), sixteen mix proportions were designed using the Taguchi orthogonal method. Five variables investigated were the water-to-binder ratio (0.24, 0.28, 0.32, and 0.36), sand-to-binder ratio (0.36, 0.46, 0.56, and 0.66), polyvinyl alcohol (PVA) fiber content (1.5%, 1.7%, 2.0%, and 2.2%) by volume, fly ash replacement (60%, 65%, 70%, and 75%) by weight, and the superplasticizer content (0.10%, 0.15%, 0.20%, and 0.25%). Each GHPFRCC specimen was subjected to a target temperature (200 °C, 400 °C, 600 °C, and 800 °C), and then measured for its thermal conductivity using a transient plane source method. The experimental results showed that the thermal conductivity of GHPFRCC decreased dramatically in the initial stage up to 400℃, then slowly decreased with temperature until 800℃. Compared with normal concrete, the GHPFRCC is relatively low in thermal conductivity and, therefore, can be used as a better thermal insulation material for infrastructures.

INTRODUCTION

Concrete is the most widely used building material in the world due to its availability, adaptability, and durability. When reinforced with steel, concrete can act as a heat barrier and provide thermal insulation for steel due to its low thermal conductivity. However, concrete is brittle in nature and prone to cracking under tensile stress. Once cracked, the exposed steel is corroded in an accelerated way, which results in further cracking in concrete [1]. In addition, high energy consumption and greenhouse gas emission during the production of cement have received increasing attention around the world [2].

High performance concrete and ultra-high performance concrete have been developed to

[1]School of Civil Engineering, Shandong Jianzhu University, Jinan, China 250101
[2]School of Engineering & IT, University of Melbourne, Melbourne, Australia 3010
[3]Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science and Technology, Rolla, USA 65409

Experimental Study on Mechanical Properties of Ultra-high Strength Concrete at Elevated Temperatures

MINGXIANG XIONG, J. Y. RICHARD LIEW and YONG DU

Abstract

This paper introduces experimental study on mechanical properties of an ultra-high strength concrete at elevated temperatures. The compressive strength on cylinders and modulus of elasticity of the ultra-high strength concrete (f_c = 166 N/mm^2) were investigated up to 800°C. The temperature dependent mechanical properties were compared with those of normal/high strength concretes provided in Eurocode 2 and ANSI/AISC 360-10, and with those of concretes in literature. The comparisons showed that the compressive strength and elastic modulus of the ultra-high strength concrete were generally reduced less than those of normal/high strength concretes at elevated temperatures, indicating higher fire resistance when it is used in structural load-bearing elements. The temperature-dependent mechanical properties are proposed to evaluate fire resistance of concrete filled tubes using the ultra-high strength concrete in high-rise buildings.

1 Introduction

Ultra-high strength concrete (UHSC) with compressive strength higher than 120MPa has been available with the development of concrete technology and the availability of variety of materials such as silica fume and high-range water-reducing admixtures. It is mainly used in offshore and marine structures and for industrial floors, pavements and security barriers but has not been used in building structures. This may be due to design concerns on its brittleness and fire resistance leading to the situations that the current standards allow the use of

M.X. Xiong[1,2], J.Y. Richard Liew[2,3,*], Y. Du[3]
[1]School of Civil and Transportation Engineering, Guangdong University of Technology, 100 Waihuan Xi Road, GuangZhou, China 510006
[2]Department of Civil Engineering, National University of Singapore, 21 Lower Kent Ridge Road, Singapore 119077
[3]School of Civil Engineering, Nanjing Tech University, NO.30 Puzhu Road(S),Nanjing, China 211816
* Corresponding author: ceeljy@nus.edu.sg

Post-Fire Residual Mechanical Properties of High Strength Concrete (HSC) Made with Basalt Aggregate

MARCELA BARROS DE SOUZA SOLLERO
and ARMANDO LOPES MORENO JR.

ABSTRACT

This paper addresses an investigation of the residual mechanical properties of high strength concrete produced with coarse basalt, limestone and granite aggregate and exposed to temperatures of 200ºC, 400ºC and 600ºC. The paper objectives are: comparatively analyze test results with data from standards and results from other authors, evidencing the influence of coarse aggregate in the material performance; and provide reduction coefficients of mechanical properties of concrete containing basalt aggregate exposed to high temperatures, which is used in many countries and have notable thermal properties, but is not addressed by the structural fire design standards.

INTRODUCTION

It is widely known that, though presenting a good performance when exposed to high temperatures, concrete's mechanical properties are impacted by them.

FIB [1] bulletin nº 38 indicates that concrete behavior during heating and cooling depends on the type of cement paste, type of aggregate, bond region and the interaction between them.

Though changes occur chiefly in the cement paste, the influence of aggregates is very intense, because they usually constitute up to 80% of the concrete volume, and affect the concrete thermal strain and thermal conductivity, restrains creep and shrinkage of the cement paste and may suffer different physical-chemical alterations due to heat, depending on their type.

Norms and bulletins that address concrete in fire situation usually present tables or diagrams relating reduction coefficients of mechanical properties of concrete with normal strength as function of temperature, distinguished by type of course aggregate.

Marcela B. S. Sollero, Faculdade de Engenharia Civil, Arquitetura e Urbanismo, UNICAMP, marcela.barros.souza@gmail.com, Rua Saturnino de Brito, 135, Barão Geraldo, CEP 13083 – 852, Campinas, SP, Brasil.
Armando L. Moreno Júnior, Faculdade de Engenharia Civil, Arquitetura e Urbanismo, UNICAMP, almoreno@fec.unicamp.br, Rua Saturnino de Brito, 135, Barão Geraldo, CEP 13083 – 852, Campinas, SP, Brasil.

Effects of Polypropylene and Steel Fibers on Permeability of Ultra-high Performance Concrete at Hot State

Y. LI and K. H. TAN

ABSTRACT

Permeability of concrete is identified as one of the key parameters controlling explosive spalling. Measurements of permeability were performed on ultra-high performance concretes (UHPC) at elevated temperature ranging from ambient temperature to 300 °C. The effects of polypropylene fibers and steel fibers were investigated. The results show that plain UHPC and UHPC with steel fibers exhibit steady increase in permeability with increasing temperature. UHPC with polypropylene fibers exhibits a sudden increase of permeability at 150 °C. The microstructure of UHPC before and after exposure to elevated temperature was investigated by conducting Field Emission Scanning Electron Microscope (FESEM) observation. The results confirm that both the channels caused by melted polypropylene fibers as well as the generated micro crack network are the major factors causing a significant increase in permeability.

1. INTRODUCTION

Compared with normal strength concrete, ultra-high performance concrete (UHPC) has superior performance such as high strength, high toughness and impact resistance, high abrasion resistance, high durability, etc. These excellent properties are due to dense microstructure on concrete. Due to superior performance, UHPC has been increasingly utilized in many civil engineering structures such as high-rise buildings, tunnels, and bridges. However, the dense microstructure makes UHPC even more vulnerable to explosive spalling in fire condition [1, 2]. Explosive spalling results in partial loss of concrete cross section and exposure of steel reinforcements to fire, which significantly compromises the load-bearing capacity of structures [3, 4].

School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore

2

鋼材料性質

1. Behaviour of High Strength Steel under Fire Conditions
2. Experimental Study of High-Strength Bolts under Combined Tension and Shear During and After Fire
3. Post-Fire Mechanical Properties of High Strength Grade 8.8 Steel Bolts

Behaviour of High Strength Steel under Fire Conditions

DOROTHY A. WINFUL[a,b,c], KATHERINE A. CASHELL[b], ADRIENE M. BARNES[c] and RICHARD J. PARGETER[c]

ABSTRACT

This paper is concerned with the material characteristics of various commercial high strength structural steels (yield strengths between 460 and 700 N/mm^2) at elevated temperatures. These steels vary in chemical composition and production route but have similar tensile properties at ambient temperature. Preliminary data of the following: proportional limit ($f_{p,\theta}$), elastic modulus ($E_{a,\theta}$), effective yield strength ($f_{y,\theta}$) based on the total strain level at 2% (in accordance with the Eurocode approach) obtained from isothermal tests are presented as reduction factors and compared with literature and the Eurocode (EN 1993-1-2). The consequences for material selection and design are also discussed.

1. INTRODUCTION

During the conceptual design stage of a project, the selection of materials and structural schemes are often governed by the requirement for solutions to be economically viable whilst equally providing a positive contribution towards the environment and society. High strength steels (HSS, defined here as materials with yield strength between 460 and 700 N/mm^2 in accordance with the Eurocode Part 1-12 [1]) have the potential to make a positive contribution towards these demands by reducing the material usage and hence weight of structural elements when employed in appropriate applications. Lighter structures lead to smaller foundations, reduced transportation costs and potentially reduced construction times and costs, as well as lower CO_2 emissions and energy use during construction.

One of the issues preventing more widespread use of HSS in structures is the lack of reliable information relating to the response of these materials at elevated temperature. Although the Eurocode does include a section for HSS [1], the guidance for fire design is based on experiments on steel with yield strengths below 460 N/mm^2. For HSS, there are limited data in the literature (e.g. [2, 3]) that present the effects of

[a]National Structural Integrity Research Centre (NSIRC), Great Abington, Cambridge, CB21 6AL UK
[b]Department of Civil Engineering, Brunel University London, Kingston Lane, UB8 3PH, UK
[c]TWI Ltd, Great Abington, Cambridge, CB21 6AL, UK

Experimental Study of High-Strength Bolts under Combined Tension and Shear During and After Fire

ANNE K. KAWOHL and JORG LANGE

ABSTRACT

Experimental studies on high-strength bolts which included both tests under tension and shear show deviating reduction of strength with rising temperatures depending on whether the bolts were loaded by tension or shear. In this paper an experimental study on high-strength bolts of the property class 10.9 under a combination of both tension and shear will be presented. Tests were carried out both under fire conditions and at ambient temperature on bolts first heated to a specified temperature and then cooled slowly to establish the post-fire performance.

INTRODUCTION

Connections are essential to the stability of a steel structure. The connections not only transfer load from one bearing member to another but, through their rigidity they also influence internal forces. During a fire the connections are exposed not only to thermal strain in addition to the internal forces at ambient temperatures; in the heating phase of a fire a connection which usually is designed to bear moment and shear receives compression from the thermal expansion of the connected member. In a later phase of the fire the strain changes to shear and tension as the connected beam hangs more or less in catenary. For the load case fire, connections therefore must have sufficient ductility. The rotational capacity depends on the different elements that form a connection, e.g. the bolts used. In addition to the load bearing capacity the load-deflection behavior is of interest.

The behavior of high-strength bolts in fire is of special interest as they obtain their enhanced strength through different heat treatments which are partially reversed in fire. Several studies on the load bearing behavior of high-strength bolts under fire have been carried out in recent years. Most of these studies, however, focus either on pure tension or pure shear tests. Those studies, which included both tests (tension and shear) show deviating reduction factors for bolt strength depending on whether the bolts were loaded by tension or shear. One of these studies is the extensive test series done by Kirby [1] on different bolts of the property class 8.8 (f_u = 800 N/mm²). At

Institute for Steel Structures and Materials Mechanics, Technische Universität Darmstadt, Franziska-Braun-Straße 3, 64287 Darmstadt, Germany

Post-Fire Mechanical Properties of High Strength Grade 8.8 Steel Bolts

MAHMOOD YAHYAI[1], ABBAS REZAEIAN[2],
VENKATESH KODUR[3], MOHAMMADREZA ESLAMI[3]
and ALIREZA POORMOHAMADI[1]

ABSTRACT

In order to understand the post-fire performance of bolted connections, it is essential to have a deep knowledge of the material behavior of all the components, including bolts, after fire conditions. Very limited research has been carried out on the behavior of high-strength steel bolts during and after fire conditions. This paper presents experimental investigations of the residual mechanical properties of Grade 8.8 bolts after exposed to elevated temperatures up to 900°C. The post-fire stress-strain curves, residual elastic modulus, yield and ultimate strengths as well as tensile failure modes of bolts were investigated. Also, the effect of factors including target temperature level, chemical composition of feedstock steels (SAE 10B21 and 10B38) and heat treatment characteristics in production process of Grade 8.8 bolts were studied. It was observed that, the bolts exhibited drastic reduction in strength after cooling down from temperatures beyond 400°C, as they lost about 50% of their ultimate strength after experiencing 800°C. Furthermore, a set of predictive equations are proposed for evaluating the residual mechanical properties of Grade 8.8 bolts after fire.

Keywords: Steel bolt, Mechanical properties, Post-fire, Residual factor, Tensile fracture, Temperature

1. INTRODUCTION

Connections in a structural system play a critical role in transferring loads from one member to the other. The integrity of a structural system may be compromised in the event of connections failure, leading to damage or even collapse of the structure. The role of bolted connections is much more crucial under fire condition; as significant fire-induced forces have to be withstood (Rezaeian and Yahyai 2015; Yahyai and Rezaeian 2015; Saedi and Yahyai 2009) [1-3]. As the critical basis of

---

[1] Department of Civil Engineering, K.N. Toosi University of Technology, Iran,
E-mail: yahyai@kntu.ac.ir
[2] Department of Civil Engineering, Shahid Chamran University of Ahwaz, Iran,
E-mail: rezaeian_a@scu.ac.ir
[3] Department of Civil and Environmental Engineering, Michigan State University, USA,
E-mail: kodur@r.msu.edu; eslami@msu.edu

3

木構造材料性質

1. Changing Failure Modes of Cross-Laminated Timber
2. External an Internal Factors Influencing the Charring of Timber – an Experimental Study with Respect to natural Fires and Moisture Conditions

Changing Failure Modes of Cross-Laminated Timber

RICHARD EMBERLEY, ALEXANDER NICOLAIDIS,
DILUM FERNANDO and JOSE L. TORERO

ABSTRACT

Cross-laminated timber relies on the adhesive layer between adjacent timber plies to provide composite action between the lamella for increased member strength and stiffness. Previous research has shown that adhesive loses normal and shear stiffness at elevated temperatures increasing the slip between adjacent timber plies. Slip in the bond layer results in reduced composite action increased deflections and a potential loss in ultimate strength in the CLT member. In order to study the effects of temperature on the flexural behavior of CLT, two series of tests were conducted. The first series focused on identifying the changing failure modes while the second series established conditions that led to those failure modes in large CLT beams. The results clearly showed the failure mode of CLT changes from timber failure to failure in the adhesive as a function of the in-depth temperatures. The adhesive failure yielded larger deflections and a loss in stiffness and ultimate strength.

INTRODUCTION

Cross-laminated timber (CLT) is an engineered mass timber product which relies on an adhesive layer between two adjacent timber plies to provide composite action of the plies for increased section strength. The crosswise layering homogenizes the timber properties in both the longitudinal and transverse directions. The adhesive layer in CLT provides composite action between timber plies while being subjected to both interfacial normal and shear forces. At ambient temperatures, the adhesive layer is typically strong enough to delay interfacial failures until the occurring of timber failures such as rolling shear or tensile failure in timber. Any loss of bond strength affecting the stiffness and strength of the adhesive could yield increases in deflection and decreases in ultimate strength due to loss of composite action due to increased slip or debonding of the bonded interface. Slip is the relative movement of two adjacent lamella apart from a complete rigid bond.

Very little research has been conducted on the relationship between adhesive behavior and the timber at elevated temperatures. Of the few studies conducted all have found that adhesive stiffness, strength, and slip are dependent primarily on the

The University of Queensland, School of Civil Engineering, Staff House Road, St. Lucia, QLD, 4072, Australia

External an Internal Factors Influencing the Charring of Timber – an Experimental Study with Respect to natural Fires and Moisture Conditions

NORMAN WERTHER

ABSTRACT

The following publication summarizes the experimental work of fire tests as well as the accompanied analytical studies conducted by the author in order to assess the influence of the initial moisture content as well as varying temperature time scenarios, including the heating- and cooling phase of a fire on the charring of timber and on the temperature profiles within timber cross sections. The outcome of this research is a simplified design approach for calculating the charring depth, and an improved material model that can be used in numerical simulations.

INTRODUCTION

In recent years, an increased interest in using timber as a construction material has been noted all over the world, driven by a discussion of energy- and resource efficiency in the building sector. Despite political initiatives, which support the use of timber, concerns and gaps of knowledge still exist, particularly related to fire safety and the performance based design process. In case of a fire, failure of loadbearing elements may cause significant human and economic losses that are not tolerated by society. Considering these aspects, several design standards such as EN 1995-1-2 [1] have been developed to assess the fire safety of timber elements and structures. In general, the basic concept of these methods is the determination of the charring depth, followed by an assessment of the structural performance of the residual cross section. For unprotected timber elements exposed to standard fire, the reduction of the original cross section by charring has a larger influence on the load-bearing capacity as the thermal softening within the remaining cross section [2]. Considering this fact, the determination of the char depth is the key to a reliable structural fire design with timber. However, several experimental studies have shown that external and internal parameters influence the charring of timber and indicate for largely scattered results.
With respect to performance based design, it becomes ever more important to better understand how the charring of timber is influenced by specific parameters such as

Norman Werther, Technical University Munich, Chair for Timber Structures and Building Construction, Arcisstraße 21, 80333 Munich, Germany.

4

防火被覆性質

1. Experimental Study of the Behavior of Steel Structures Protected by Different Intumescent Coatings and Exposed to Various Fire Scenarios
2. An Experimental Study of the Damage Modes of Fireproof Coatings Under Complex Loads

Experimental Study of the Behavior of Steel Structures Protected by Different Intumescent Coatings and Exposed to Various Fire Scenarios

ANDREA LUCHERINI, RAZVAN-IOAN COSTA,
LUISA GIULIANI and GRUNDE JOMAAS

ABSTRACT

Three different experimental setups corresponding to three different fire scenarios were used to investigate how different heating conditions and heating rates affect the behavior of two different thin intumescent coatings (solvent-based and water-based paints, respectively). The results confirm that the current procedure for the design of intumescent coatings has shortcomings, as different paints have different performances according to the heating conditions and, in particular, according to the fire's heating rate. The tested water-based paint had better performance for low heating rates, while the tested solvent–based paint had better performance for high heating rates. However, for really low heating rates the solvent-based paint did not activate or provide proper insulation.

INTRODUCTION

Thin intumescent coatings have become the dominant passive fire protection system used to protect structural steel from fire [1]. These coatings swell on heating to form a highly insulating foamed char, hence preventing steel from reaching critical temperatures that could cause structural failure. The increasing growth of intumescent coatings in the built environment is associated with the low impact in the attractive appearance of bare steel structure, with their ability to be applied off site, and with their potential for offshore applications [1]. Intumescent coatings are thermally reactive fire protection materials and they are usually composed of a combination of organic and inorganic components bound together in a polymer matrix [2, 3].

Current design procedures for assessing the amount (i.e. thickness) of intumescent coating needed to protect steel profiles exposed to fire are based on standard fire tests, in particular the cellulosic standard fire curve [4, 5]. However, several studies have highlighted that the behavior of intumescent coatings not only depends on the temperature, but it can be highly influenced by other conditions of any given fire event, for example the heating rate [2, 3, 6, 7]. As a consequence, the current design procedures used for intumescent coatings are fundamentally based on the standard fire exposure, and hence cannot be

Lucherini A., Costa R.I., Giuliani L. and Jomaas G., Technical University of Denmark, Brovej, Building 118, 2800 Kgs. Lyngby, Denmark; email: grujo@byg.dtu.dk

An Experimental Study of the Damage Modes of Fireproof Coatings Under Complex Loads

S. W. CHEN, Y. J. WANG, L. M. JIANG and A. S. USMANI

ABSTRACT: Fire proof coatings used as passive fire protection in steel structures may sustain damage when subjected to seismic, blast or impact action. Complex states of stress exist within the coating as well as at the interface between the coating and the surface of the steel member. This paper reports an experimental study on damage modes of different fireproof coatings when steel columns under complex loads. Behavior of cementitious coating and intumescent coating are compared. Different failure modes of these two coatings are observed.

Keyword: Cementitious fireproof coating; intumescent fireproof coating; complex loads; failure modes

1 Introduction

Post-earthquake fire is believed to be one of the main secondary disasters after an earthquake[1]. It may cause greater losses than the loss caused by the earthquake itself [2~3]. Steel structures are generally considered to be sustainable because of their light weight, recyclability, good seismic performance and speed of erection, however they are perceived to possess poor fire resistance as at 550℃, the yield strength and ultimate strength may drop to half of those at room temperature[4]. Therefore steel structures unprotected against fire are considered to be vulnerable to elevated temperatures and liable to failure or collapse [4]. The traditional approach to mitigate this vulnerability has been to insulate steel structural members from the effect of fire by using appropriate form of passive fire protection (PFP) material.

Cementitious fireproof coating[5] is one of the most widely used PFP, usually spray applied to structural members to protect steel frames buildings because of its low density, low thermal conductivity (around 0.1 W/m K), low cost and non-toxic emissions in fire. However, this type of fireproofing material is brittle and fragile with a low tensile strength and a great deal of variation in its mechanical properties. Thus, cracking and interfacial debonding may occur under the action of seismic, blast or impact action leading to impaired fire resistance of steel structures [6,7]. Dwaikat and Kodur [8] present parametric studies conducted for modelling the fracture and delamination of cementitious coating on insulated steel plates subjected to static and impact loads based on a mixed 2D cohesive zone finite element (CZFE) scheme.

In recent years, a programme of fundamental research[9-13] has been undertaken by the authors at Tongji University in order to develop a method for evaluating the damage in cementitious coatings on structural steel members subjected to external

Corresponding author: Suwen Chen, PhD, Associate Professor, State Key Laboratory for Disaster Reduction in Civil Engineering, College of Civil Engineering, Tongji University, Shanghai, 200092, P.R. China, Tel: +86-21-65982975-16, Fax: +86-21-65983431, Email:swchen@tongji.edu.cn

Yanjun Wang, MA Eng, College of Civil Engineering, Tongji University, Shanghai, 200092, P.R. China. Email: 133273@tongji.edu.cn

Liming Jiang, PhD, Post-Doctoral Research Assistant, Brunel University London, UK. Email: liming.jiang@ed.ac.uk

Asif Usmani, PhD, Professor, Brunel University London, UK. Email: asif.usmani@brunel.ac.uk

5

樓版及複合鋼梁實驗

1. Modelling the Thermal and Structural Performance of a Concrete Column Exposed to a Travelling Fire – Tisova Fire Test
2. The Performance of Structural Steel Beams Subject to a Localized Fire
3. The Effects of Load Intensity and Restraint on the Fire Resistance of Steel and Composite Beams
4. Development and Modification of Yield Line Patterns in Thin Slabs Subjected to Tensile Membrane Action
5. Evaluation of Composite Steel-Concrete Slab Performance Subjected to Travelling Fire: A Case Study

Modelling the Thermal and Structural Performance of a Concrete Column Exposed to a Travelling Fire – Tisova Fire Test

DAVID RUSH[1], DAVID LANGE[2], JAMIE MACLEAN[1], and EGLE RACKAUSKAITE[3]

SUMMARY

The Tisova Fire Test was a large real scale fire test conducted in the Czech Republic in January 2015 inside of a 4-storey concrete frame building, with concrete and composite deck floors. The ground floor test compartment had a total area of ca. 230m^2 with a height of 4.4m. The fire compartment included four columns from the original 1958 concrete construction, one of which was instrumented retroactively for temperatures, chosen due to its higher likelihood of observable thermal and structural response. This paper presents selected results from the thermal environment around, and the thermal response of, the column showing the variability of temperatures through the compartment height. The paper proceeds to model the thermal response of the column from 1) the real fire scenario, and 2) equivalent areas under the standard fire curve. These thermal profiles are then used to assess the reduction of the columns cross-sectional capacity, and shows that using equivalent fire durations is not an appropriate method to calculate the thermal and structural response of concrete columns exposed to a travelling fire.

INTRODUCTION

Current fire engineering design guidance (e.g. [1]), in general, assesses single structural elements and their response to fire on a pass/fail assessment usually consisting of prescribed fire resistance criteria and times. This assessment is usually based on a standard fire that represents only one fire out of a range of possible fires which may occur, and may not represent the most onerous (or more realistic) fire insult that a structure might experience [2]. The tests are also limited in their ability to represent fires within large compartments such as a travelling fire, and so representation of fire severity have been developed (i.e. [3]).

Modelling of concrete elements and structures to non-standard fires has shown that long durations of some travelling fires [4] or parametric fires [5] can have significant effects on the response of concrete structures. However the validity of these models

[1]BRE Centre for Fire Safety Engineering, University of Edinburgh, UK.
[2]Technical Institute of Sweden SP, Boras, Sweden
[3]Imperial College London, UK

The Performance of Structural Steel Beams Subject to a Localized Fire

LISA CHOE, SELVARAJAH RAMESH, CHAO ZHANG and JOHN GROSS

ABSTRACT

This paper presents the results from the open flame, localized fire tests conducted on 6.17 m long, simply supported W16×26 beam specimens. The cross sections at midspan (i.e., expected plastic hinge zone) of the beam specimen were directly exposed to the natural gas fire. Two different tests were conducted: (1) fire-thermal tests to evaluate the effects of the prescribed heat release rates (HRR), provided by the 1 m^2 natural gas burner, on the thermal responses of the specimen and (2) structural-fire test to evaluate the fire effects on the overall behavior and the load-bearing capacity of the specimen. The test results indicated that the prescribed heat release rates from the burner affected the heating rate of the specimen. When the HRR-time relationship of the burner followed a step function, the fire-exposed region of the beam specimen was heated essentially linearly with increasing time of fire exposure. When the HRR was set to a target magnitude of 400 kW throughout the test, the fire-exposed region was heated nonlinearly until it reached a steady-state temperature condition. When the beam specimen was subjected to linearly increasing flexural loads at a maintained HRR of 700 kW, combined flexural and lateral torsional failure of the specimen was exhibited. The lateral deformations in the compression flange at the fire-exposed critical sections initiated at 124 ± 5 kN-m, which is 39% of the plastic moment capacity at room temperature. The peak moment capacity was 171 ± 9 kN-m (54 % of the plastic moment capacity at room temperature), while the maximum temperature was 642 ± 28 °C at the HRR of 700 kW. The test results from the present study can be used for developing or calibrating analytical models, which can be eventually used for evaluating the performance of structural members subjected to a localized fire.

INTRODUCTION

The 6.17 m long W16×26 beam specimens subjected to a localized fire were tested at the National Fire Research Laboratory (NFRL) [1] of the National Institute of Standards and Technology (NIST). The main objective of these tests was to commission the structural fire experimental measurement capabilities of the newly constructed laboratory. A secondary objective was to generate data set for validation of analytical models. The experimental tests were divided into two parts: the fire-

National Institute of Standards and Technology, 100 Bureau Dr, Gaithersburg, Maryland 20899, USA
lisa.choe@nist.gov, selvarajah.ramesh@nist.gov, chao.zhang@nist.gov, john.gross@nist.gov

The Effects of Load Intensity and Restraint on the Fire Resistance of Steel and Composite Beams

FARID ALFAWAKHIRI[1], CHARLES J. CARTER[2], ROBERT M. BERHINIG[3], PATRICK ZEEVELD[4], FREDERICK E. HERVEY[4] and LUKE C. WOODS[4]

SUMMARY

The paper presents the results of sixteen fire resistance tests (in accordance with ASTM E119 and ANSI/UL 263 standards) on structural steel beams and composite steel/concrete beams conducted by the authors in 2015 at the Underwriters Laboratories facility in Northbrook, Illinois. The described experimental program was designed to investigate the effects of load intensity and restraint on the fire resistance of steel and composite beams in the context of contemporary construction materials and structural design standards. In terms of the scope and the range of investigated parameters, such experimental study was carried-out in North America for the first time. The test results confirmed the beneficial effects of reduced loads and restraint on the performance of beams in standard fire resistance tests and quantified these beneficial effects in terms of critical (failure) temperatures. The tests results also confirmed and quantified the long existing knowledge about non-composite structural steel beams performing much better than comparable composite steel/concrete beams in fire resistance tests. The generated experimental data will be used to validate numerical models, conduct parametric studies and develop simplified correlations for load intensity versus fire resistance time (and/or protection thickness). It will be of interest to certification laboratories, product developers and the broader structural fire protection design community.

INTRODUCTION

Fire resistance tests of loaded beam specimens, with a representative section of floor or roof construction not exceeding 7 ft (2.1 m) in width, were first adopted in North America in the early 1970s [1]. Earlier, standardized testing of loaded beams

[1]American Iron and Steel Institute, 25 Massachusetts Avenue, NW, Suite 800, Washington, District of Columbia 20001, U.S.A.
[2]American Institute of Steel Construction, One East Wacker Drive, Suite 700, Chicago, Illinois 60601-1802, U.S.A.
[3]Berhinig Services LLC, 1310 Chestnut Avenue, Arlington Heights, Illinois 60004, U.S.A.
[4]Underwriters Laboratories LLC, 333 Pfingsten Road, Northbrook, Illinois 60062, U.S.A.

Development and Modification of Yield Line Patterns in Thin Slabs Subjected to Tensile Membrane Action

FABIEN QUICHAUD, IAN BURGESS and SHAN-SHAN HUANG

ABSTRACT

It is widely recognized that composite floor slabs experiencing large displacement develop a central zone of hydrostatic membrane tension, surrounded and equilibrated by a ring of membrane compression around the periphery. This mechanism, known as tensile membrane action, can greatly enhance the load-bearing capacity of a slab compared with that defined by yield line analysis. This is a very useful effect in cases where large deflections can be accepted, particularly in fire-resistance design of composite slabs, since the strength enhancement permits some beams to be left unprotected. Studies of tensile membrane action in the 1960s led to the development of several methods to define slab load capacity under large displacement. The method due to Hayes [5] has become the most widely accepted, and was adopted by Bailey [1, 2] in developing the BRE method for fire-safe design of composite floors. Based on observations from the Cardington fire tests and on assumptions concerning yield line patterns and membrane stresses, it calculates the load-carrying enhancement of a slab as a function of its deflection [2]. It also postulates a deflection limit at which the maximum acceptable strain in the rebar is reached. On close examination, however, several hypotheses, such as the assumed failure mechanisms, seem illogical.

The BRE method assumes that a common observation, of a through-depth crack forming across the central short-span of the slab, represents the limit state for such slabs. However, it has been observed that similar cracks can also appear at the intersections of the yield lines, or even not appear at all [3]. This paper proposes a simple way to define the deflection at which the through-depth crack forms, and where on the slab it appears. Based on consistent kinematic assumptions, it calculates the tensile stresses at key points of the slab [4], and predicts the position and displacement at which through-depth cracking occurs.

INTRODUCTION

The Cardington Fire tests on a full-scale composite building in 1995-96 clearly showed composite floor slabs resisting much higher temperatures than those for which they had been designed [1]. This enhancement was recognized as being due to tensile membrane action (TMA); at large displacement, the slabs experienced high double

University of Sheffield, Department of Civil & Structural Engineering, Sir Frederick Mappin Building, Mappin Street, Sheffield, S1 3JD, United Kingdom.

Evaluation of Composite Steel-Concrete Slab Performance Subjected to Travelling Fire: A Case Study

RUI R. SUN and BERNICE V. Y. WONG

ABSTRACT

This paper presents a case study which aims to contribute a better understanding of the fire performance of composite slab panel structural under non-uniform fire. A travelling fire which simulates the procedure of fire spread over a large office compartment is introduced. The coupled CFD modelling and heat transfer model is used for the fire and thermal analysis. The elevated composite slab temperatures are applied to finite element model for structural fire analysis by using ABAQUS. The phenomenon of tensile membrane action in partially fire protected composite slab when subjected to travelling fire is presented. It has been observed that the predicted office compartment fire has slower temperature growth rate than that of the ISO 834 standard fire as well as the parametric fire. The study has found out that the traditional structural fire engineering design may lead to over-conservative prediction with respect to composite slabs structural fire performance under travelling fire.

INTRODUCTION

Design fire for the elevation of structural performance in case of fire has been outlined in Eurocodes, assuming a homogeneous temperature distribution throughout the entire fire compartment, regardless of its size. However in reality, fire do not burn simultaneously but spread across floor plates, from its ignition source travel to adjacent combustible surfaces by direct flame contact. There are a number of investigations concerning tensile membrane action in composite floor when under homogeneous compartment fire. The composite slab behavior under travelling fire however has not been extensively studied. In this paper, a case study has been carried out to examine the behavior of this form of structural action under the exposure of travelling fire and whether the current design method to this situation gives a more-conservative assumption.

Rui R. Sun, MMI Engineering, KMD Media Centre, Wellington Circle, Aberdeen, AB12 3JG, UK.
Bernice V. Y. Wong, Ramboll Fire, 240 Blackfriars Road, London SE1 8NW, UK.

6

實驗量測設備與方法

1. Temperature and Strain Measurements with Fiber Optic Sensors for Steel Beams Subjected to Fire
2. Thermographic Digital Image Correlation (TDIC) Measurements of Mechanically-Loaded Structures

Temperature and Strain Measurements with Fiber Optic Sensors for Steel Beams Subjected to Fire

YI BAO[1], YIZHENG CHEN[1], MATTHEW S. HOEHLER[2], CHRISTOPHER M. SMITH[2], MATTHEW BUNDY[2] and GENDA CHEN[1,*]

ABSTRACT

This paper presents measurements of high temperatures using a Brillouin scattering based fiber optic sensor and large strains using an extrinsic Fabry-Perot interferometric sensor for assessing the thermo-mechanical behaviors of simply-supported steel beams subjected to combined thermal and mechanical loading. The distributed fiber optic sensor captures detailed, non-uniform temperature distributions that are compared with thermocouple measurements resulting in an average relative difference of less than 5 % at 95 % confidence level. The extrinsic Fabry-Perot interferometric sensor captures large strains at temperatures above 1000 °C. The strain results measured from the distributed fiber optic sensors and extrinsic Fabry-Perot interferometric sensors were compared, and the average relative difference was less than 10 % at 95 % confidence level.

INTRODUCTION

During a fire, the load capacity and stability of steel structures can significantly degrade due to adverse temperature-induced deformations and reduced material properties [1]. To assess the thermo-mechanical conditions of a structure, both temperatures and strains must be known. The current state of practice in experimental fire testing is to measure the temperature and global deformation of specimens and to use analytical models to understand the behavior of the member. Effective tools are lacking to directly measure strains in steel members subjected to fire, reliably and accurately.

Fiber optic sensors have drawn intense research interest in the past decade due to their unique advantages, such as immunity to electromagnetic interference, small size, light weight, and excellent durability and resistance to harsh environments. However, their application to structures in fire has not yet been fully explored. Conventional grating-based fiber optic sensors degrade significantly when heated over 300 °C and typically fail around 600 °C [2], which limits their application in fire. Although their temperature operation range can be increased to 1000 °C through means such as the regenerated fiber Bragg grating technique [2], the grating sensors do not provide spatially distributed measurements, but rather a point

Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science and Technology, 1870 Miner Circle, Rolla, MO 65409, USA
National Fire Research Laboratory, National Institute of Standards and Technology, 100 Bureau Drive, Stop 8666, Gaithersburg, MD 20899, USA
*Corresponding to Dr. Genda Chen. Email: gchen@mst.edu, Phone: (573)341-4462

Thermographic Digital Image Correlation (TDIC) Measurements of Mechanically-Loaded Structures

JONATHAN L. HODGES, CHRISTIAN RIPPE, SCOTT W. CASE and BRIAN Y. LATTIMER

ABSTRACT

This research examined the use of Thermographic Digital Image Correlation (TDIC) in fire testing with flames in the field of view. The error and uncertainty in the deformation measurements obtained via TDIC with fire in the field of view were reduced by ensuring the grayscale histogram of the CCD images was neither under-saturated nor oversaturated once fire was present. Quantitatively, this corresponded to the greyscale histogram having a mean value between 13-91 out of 255 and a kurtosis between 2.7-10.7 without the fire present. Results obtained from testing using this setup were found to reduce data loss due to overexposure when compared to results obtained using arbitrary light conditions. Thus, future investigators may reduce the error in the system for live fire testing before exposing the sample to fire by setting up lighting and camera settings to obtain histograms in this range.

INTRODUCTION

In structural experiments involving fire it is often desirable to measure both deformation and temperature fields of load-carrying members being tested. Traditionally these measurements are obtained using physical methods such as string potentiometers and thermocouples. Obtaining full field measurements requires an array of these devices along the specimen. Unfortunately it can be difficult to attach these devices without affecting the physical system. In addition, it is often difficult to determine where failure may occur so that instrumentation can be appropriately positioned. Non-contact measurement methods are desirable to reduce setup issues and ensure the appropriate data is captured.

Numerous non-contact measurement methods have been proposed for obtaining either deformation or temperature field measurements; however, few have been proposed which simultaneously measure both quantities. Thermographic Digital

Jonathan L. Hodges, Virginia Tech, 635 Prices Fork Road, Blacksburg, VA 24061
Christian Rippe, Jensen Hughes, Inc., Blacksburg, VA 24061
Scott W. Case, Virginia Tech, 635 Prices Fork Road, Blacksburg, VA 24061
Brian Y. Lattimer, Jensen Hughes, Inc., Blacksburg, VA 24061

7

數值分析新元素

1. Component-Based Element of Beam Local Buckling Adjacent to Connections in Fire
2. Constitutive Modelling of Ductile Metals at High Temperature

Component-Based Element of Beam Local Buckling Adjacent to Connections in Fire

GUAN QUAN, SHAN-SHAN HUANG and IAN BURGESS

ABSTRACT

An analytical model based on the yield line mechanism [1] has been proposed by the authors to predict the beam-web shear buckling and bottom-flange buckling in fire. This paper described the development of a component-based element considering both buckling phenomena at the beam-ends, based on this analytical model. The component-based buckling element consists of top springs and bottom springs, all of which are capable of dealing with loading-unloading-reloading cycles. This new component-based element has been implemented into the software *Vulcan,* adjacent to the existing component-based connection element. An example case using a single-span beam has been analysed in *Vulcan.* The modelling results have been validated against finite element modelling using *ABAQUS,* indicating that the newly developed component-based buckling element is of good accuracy to reflect the behaviour of local buckling phenomena. Comparison of the structural responses of the beams with and without the buckling element in *Vulcan* has been carried out. This comparison shows that with and without the buckling element does make a difference in the modelling results. This indicates the potential effects of the local buckling at beam ends on the connected joints and columns and on the entire frames at elevated temperatures.

Keywords: Component-based Model, Shear Buckling, Bottom-flange Buckling, Fire

INTRODUCTION

The investigation of the collapse of "7 World Trade" as part of the events of 11 September 2001 in the New York City [2] indicated that the connections are among

Guan Quan, Department of Civil and Structural Engineering, University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, United Kingdom.
Shan-shan Huang, Lecturer, Department of Civil and Structural Engineering, University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, United Kingdom.
Ian Burgess, Professor, Department of Civil and Structural Engineering, University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, United Kingdom.

Constitutive Modelling of Ductile Metals at High Temperature

PAWEL WOELKE, RYAN ANDERSON, BADRI HIRIYUR and NAJIB ABBOUD

Constitutive behaviour of ductile metals subjected to thermo-mechanical loads associated with a fire condition as well as small-to-medium rate mechanical loads is discussed in this paper. Effective analysis and design of structures in fire require material models that are valid over a wide range of stresses, strain rates, loading and unloading cycles and temperatures. Thermal loading of metals results in a slow, creep-dominated behaviour, which can lead to local or global component failures and progressive collapse. The collapse mechanism for structures and their components, once initiated, occurs at much higher strain rates than creep. A comprehensive modelling framework that allows simulation of large-scale metal structures subjected to a wide range of stresses, strain rates and temperatures is presented. An advanced viscoplastic constitutive model is developed based on micromechanical material failure mechanisms and experimentally observed time- and temperature-dependent material behaviour. This model (*WAifire*) allows bridging the time-scale gap between creep-dominated behaviour and resulting thermo-mechanical stiffness and strength degradation on the one hand, and the high strain rate deformation and fracture caused by structural collapse on the other hand.

Keywords: Fire, Constitutive modelling, Thermo-mechanical coupling, Structural Collapse

1 Introduction

This paper gives a brief summary of the new thermo-mechanical constitutive model for ductile metals subjected to mechanical stresses and transient temperature condition caused by fire. The model takes into account the influence of stress triaxiality, normalized Lode angle and thermal material softening caused by the fire condition. The material model itself is applicable to any ductile metal with failure governed by nucleation, growth and coalescence of voids.

The theoretical development and implementation of the model into dynamic explicit finite element codes NLFlex and EPSA [8, 9] has been completed by Thornton Tomasetti - Weidlinger Applied Science (TT-WAS).

2 Material constitutive model

The new material constitutive model [1, 2, 9, 10] covers a wide range of stresses, strain rates and temperatures. One of the key advantages of the proposed model is its applicability and accuracy of the solution with different levels of strain rates ranging from thermally activated creep-dominated behaviour ($\dot{\varepsilon} = 10^{-6}/s$) to high strain rate response of the material subjected to dynamic loads ($\dot{\varepsilon} = 10^{1}/s$). Applicability to such a wide range of strain rates offers a significant advantage for

Thornton Tomasetti - Weidlinger Applied Science, 40 Wall Street New York, NY 10005-1304, USA
PWoelke@ThorntonTomasetti.com, RAnderson@ThorntonTomasetti.com,
BHiriyur@ThorntonTomasetti.com, NAbboud@ThorntonTomasetti.com