行政院國家科學委員會專題研究計畫 期中進度報告

內埋式光纖感測器研究(2/3)
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內埋式光纖感測器研究(2/3)

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中　華　民　國　96 年　5 月　15 日

摘要

複合材料具有質輕，比強度高，耐酸鹼腐蝕，耐疲勞負載等優點，使用過程中複材內部產生微損傷不容易早期發現；將導致損傷擴展，並可能造成突發且災難性的破壞！因此，近來複合材料的研究，已有朝向內埋感測器的智慧型材料/結構的方向發展的趨勢。目前已有一些應用於航太結構中的研究，將光纖埋入機身各部，形成可即時監控的智慧型結構，以增加航空器飛行的安全。

光纖感應器較不受電磁雜訊及磁場干擾，抗腐蝕， 耐高溫，疲勞壽命長，長期穩定性佳，適於對長期監測材料並可用作長距離通訊多點量測，光纖徑細質輕，且與高分子材料之相容性很好，適宜埋入高分子基複合材料中以進行材料內部結構完整性及溫度等之監測與分析，不會造成脫層，內埋於複合材料之光纖感測器可自成化階段監控各種製程參數，可監控在整個構件壽命所實際經受之施力，遇到過大之負載，可馬上發出警訊，適時安排預防性檢查及維修，避免意外破壞之發生；另可掌握破壞之位置，並監控其發展，從而對殘餘壽命作較準確之評估；對於具有活動控制面(active control surfaces)之智慧型航太結構，因對飛行時受力狀況有即時掌握，可供用作活動面之智慧型控制，使飛行效率增加。

眾多光纖感測器中，本計劃採用光纖布拉格光柵，光纖光柵因為利用波長作為調變的參數，比起利用光強度調變來得穩定，測量也比利用相位調變來得容易與便宜，光纖光柵所形成的波長的變化，是導因於光柵所在的區域應變及溫度的變化，複合材料內部如產生破壞，會形成破壞區域附近應變變化，從而使光柵波長頻譜發生變形與漂移，然波長頻譜變形與漂移與破壞機制與破壞程度之間的關系，卻因此方面研究的缺乏，目前仍不清楚，本計劃為三年期計劃的第二年，利用第一年所建立的訊號擷取系統以及光纖感測器鑲埋技術，進行複合材料積層板疲勞破壞的監測，透過使用超音波C-scan，放射線照相以及破壞性顯微觀察，來解讀光柵波長頻譜變形與漂移所代表的破壞機制與破壞程度。

關鍵詞：內埋式光纖感測器，布拉格光柵，複合材料內部破壞監測，疲勞破壞監測。

Abstract

Polymeric composite materials have better specific stiffness/strength, corrosion resistance, and most importantly, their directional properties may be tailor made. They are however prone to develop internal damage caused by tool drop, bird-strike, hail storm and so on. Cyclic loading during service may induce subsurface defects. These insidious defects may grow during service and eventually lead to catastrophic failures. If online monitoring of the emergence and development of these defects is possible, the safety and reliability of composite structure may be much improved.

Although the detection and examination of internal defects has been under investigation for many years, the available techniques such as X-ray radiography, ultrasonic scan, modulus degradation etc still have many serious limitations. Of these the most important limit is that observation is only indirect and difficult to be applied to online real time monitoring. On the other hand, optical fiber sensors can give real time response, free of electromagnetic interference, long fatigue life, high temperature resistant and is capable of multipoint measurement on the same fiber. Optical fiber has a small diameter and may be embedded inside a composite material and literally come into contact or at least into very close proximity of the internal defects.

When internal damages occur in a polymeric structure, the waveform spectrum of an embedded fiber Bragg grating will deform and shift. The relation between this deformation and shifting with the mechanisms and extent of damage is still not clear. The current project is the second year of a three year project. In this year, we make use of the data acquisition system and the technique of fiber sensor embedment established in the first year to monitor the development of fatigue damage in carbon fiber/epoxy composite laminates. Ultrasonic C-scan, radiography and destructive optical microscopy are employed to visualize the nature and extent of the fatigue damage at different stages of life. These are compared with the deformation and shifting of the spectrum reflected from the fiber grating sensor. The current progress for the second year will be summarized in this brief report.

Keywords: Embedded fiber Optic sensor, Fiber Bragg grating, internal damage monitoring, Embedded fiber Optic sensor.

研究計畫之背景及目的

複合材料具有質輕、比強度高、耐酸鹼腐蝕、耐疲勞負載等優點，是繼傳統金屬材料以來，應用最廣的材料之一，其應用範圍包括土木工程、海洋工程、民生工業、航太工程、飛機蒙皮、交通工具…等。其中纖維積層板複材(fiber laminar composites)因其疊層具有方向性，可應不同使用需求作彈性設計，有其特殊的實用價值，因此受到廣泛地研究。

在使用過程中，當複合材料受到撞擊時，或受應力集中、循環應力等影響，材料內部便會開始產生微損傷[1-4]，這些損傷在表面無法以肉眼看出，在損傷大幅發展以前，無論以間接的勁度遞減方法 [5, 6]，或以各種超音波掃描[3,4,7]、X-ray 照相[3,4,8]、電子光斑[9,10]等直接檢測方法，往往也因靈敏度不足而無法發現早期的破壞；但材料的完整性已有減損，且早期的微損傷可成為進一步破壞之誘導因子，在長期受外力作用後，將導致損傷大規模擴展，並可能造成突發且災難性的破壞！因此，如何精確掌握複材料使用之損傷發展，對於提高材料使用的安全性相當重要。另一方面，由於複合材料領域的發展已漸趨成熟，不但已掌握製程技術，各種疊層的特性探討也有許多完整的研究成果，因此，近來複合材料的研究，已有朝向內埋感測器的智慧型材料/結構的方向發展的趨勢。目前已有一些應用於航太結構中的研究，將光纖埋入機身各部，形成可即時監控的智慧型結構，以增加航空器飛行的安全。

光纖感測器

近年來，各種光纖感測器，尤其是布拉格光柵(FBG) 使用在結構量測之應用開始受到注意[11]。國外有嘗試應用至航太結構[12]，土木結構如橋樑及建築結構體[13-16]，核電廠管路[17,18]，海上鑽油台[19]，船桅[20]，軌道工程[21] ，腐蝕感測[22]等。與傳統感測器如應變計、壓電材料相較，光纖感應器有以下幾項優點：(一) 較不受電磁雜訊及磁場干擾，適於嚴格的環境要求，如核電廠[27,28]。 (二) 徑細質輕，且與高分子材料之相容性很好，不會造成脫層，適宜埋入高分子基複合材料中[23,24]，以進行材料內部結構完整性及溫度等之監測與分析，這是應變計或壓電感測器所無法做到的。 (三) 抗腐蝕，適於深海工程及化學腐蝕環境。 (四) 耐高溫，一般電子應變計無法在高溫中進行。 (五) 疲勞壽命長，長期穩定性佳，適於對長期監測材料。(六) 因光纖可用作長距離通訊，因此光纖感測器相關技術極有機會發展出長距離、多點量測的，目前也已有此方面之研究在開展[25-28]。

內埋式光纖感測器之優點

前述各種直接觀測複材結構內部破壞的方法，不單靈敏度解析度不足以發現早期的破壞，其使用也受到很多限制，無法於結構使用時作即時線上監控。至於如勁度遞減的間接方法，雖容許即時線上監測，但如採用傳統之感測器如應變計或壓電材料，如採內埋方式，則其本身即為一嚴重之脫層缺陷，並不可行，採外置方式，則須提防其受撞擊，腐蝕等破壞，感測器本身在反覆循環之施力下壽命亦有限，更有甚者，對於如航太應用等牽涉到高速運行的結構，結構之空氣動力學流線外型，常不容外置感測器監測破壞。如果採用內埋之光纖感測器，則一方面已初步證實內埋式光纖感測器可在破壞初期發現異常[29-31]，另一方面，光纖之疲勞壽命遠較應變計等長，也不影響航太結構之流線外型，即時線上監測亦容易進行，而且監測可自製程時即開始，並持續使用至壽命之終結，其可能之結果與優點有:

一、自成化階段之各種製程參數可以控制得更好，確保先天缺陷發生之可能性降至最低，內部之預應力或殘留應力完全受到掌控，構件之出廠品質有所保證。

二、整個壽命所實際經受之施力(lifetime service loading) 完全受到監控，可作為設計數據之反饋，可供在不影響安全可靠度下降低相關之安全係數。

三、即時線上監測受力狀況，遇到超過設計容許之負載，可馬上發出警訊，適時安排預防性檢查及維修，事前因有足夠之資訊來規劃維修計劃，故可有效降低 downtime 之時間，並避免意外破壞之發生。

四、適時發現破壞，掌握破壞之位置，並監控其發展，隨時掌握破壞之程度。

五、因有準確之受力歷史及內部缺陷狀況，可以對殘餘壽命作較準確之評估。

六、對於具有活動控制面(active control surfaces)之智慧型航太結構，因對飛行時受力狀況有即時掌握，可供用作活動面之智慧型控制，使飛行效率增加。

有關內埋光纖感測器對複材內部損傷監測之研究[30,31,32-36]，對於深入掌握量測到之頻譜訊號與破壞之關連的研究，目前仍甚為缺乏，本計畫即擬填補此一缺口。自 1998 起即有相關，針對 FBG 在複材變形、破壞之感測，以期達到智慧型材料結構的理想[29-38]，文獻[37,38]試圖以埋入布拉格光柵研究複材成化之殘留應力，用殘留應力來解釋成化後所產生之雙峰效應[29]，文獻[32-38] 正嘗試應用內埋布拉格光柵感測器監測複材之內部損傷，然至，截至目前文獻所探討過的僅限單軸向或 cross-ply 複材，牽涉到的破壞機制為比較單純的基材裂紋，對於疲

勞破壞等所引起較複雜的內部損傷的監測以及判讀，目前仍無具體的掌握與了解，本計劃本年度即進行此方面的嘗試。

實驗方法

光纖布拉格光柵感測器及長周期光柵是利用側寫法以準分子鐳射在摻鍺-硼光纖中形成，長周期光柵另在雙層纖殼的摻鍺-磷光纖中形成，布拉格光柵的反射率約為 99%，其中心波長在1540 至 1550nm 之間, 長周期光柵的中心波長則為 1535nm, 光柵頻譜利用 Anritsu MS9710C 頻譜分析儀量測。

複合材料積層板利用 T300/3501 炭纖維環氧樹脂預浸布作 16 層（$[-45/90/45/0]_{2s}$）積疊而成（見圖一），積層板裁切成 25.4mm 寬，200mm 長的疲勞試片，試片中心鑽一 6.3mm 直徑的圓孔，光纖光柵在積層時即布放在未來圓孔前沿 1.5mm 位置，自此每隔 1.5mm 布放一個，共布放 4 個如圖一所示。疲勞測試以 1.5kN 至 15kN 之間，頻率為 4Hz 的循環力量進行，疲勞負載施加一定次數，當光纖頻譜出現變化時，即中止實驗，以超音波 C-scan，放射線照相及破壞性顯微觀察檢視破壞的情形。

結果與討論

長周期光柵特性探討

本計劃比較了兩種長周期光柵，分別是在單層纖殼（single cladding）與雙層纖殼（double cladding）光纖中形成者，采用後者，是因為在第一年工作中發現單層纖殼中的長周期光柵經鑲埋在高分子材料後，光柵的效應便不復存在，但如利用雙層纖殼，則鑲埋後仍可保有長周期光柵的效應。長周期光纖光柵經受溫度變化的頻譜行為特性是將光纖自由懸吊在爐子中加溫，量測不同溫度時光柵頻譜的漂移量，至於其經受應變後的特性，則是將光纖黏貼在複材，施加不同應變，記錄光柵頻譜的漂移量，兩種長周期光柵的溫度與應變靈敏度如表一，此方面的結果已於 2006 年十月於美國波士頓舉辦的 SPIE Optics East- Photonics for Applications in Industry, Life Science and Communications 研討會中發表。

表一：兩種長周期光柵的溫度與應變靈敏度

Fiber gratings	**$K_{T,}$** 溫度系數. **pm/^oC**	**Kε,** 應變系數. **pm/με**
單層纖殼長周期光柵	**-284**	**1.59**
雙層纖殼長周期光柵	**29.7**	**0.8**

從上表可見，雙層纖殼長周期光柵的溫度靈敏度約為單層纖殼長周期光柵的十分之一，從壞的方向想，靈敏度較差不利於精確的量測，但從好的方向想，則因其波長對溫度的漂移較低，所以可以量測的有效溫度範圍也較大，此點對於需要高速量測，要利用到本計劃第一年度所開發的能量調變的方法而言，更為重要，所以雙層纖殼長周期光柵其實代表一個對溫度及應變敏感度較為平衡的組合，當量測應變時，較不易受到輕微溫度改變而影響應變量測的準確度。

極早期疲勞破壞的監測

為監測早期的疲勞破壞，疲勞試片每隔 500 循環周次即停機進行一次超音波 C-scan 並記錄一次光纖光柵的頻譜，首 500 周次後，最靠近圓孔邊緣的光柵頻譜已出現變形與漂移的現象，接下來每 500 週次後的頻譜，持續發生變形與漂移，然而超音波 C-scan 並未顯示破壞有所增長的情形，圖二比較施加 5000 週次前後光纖光柵頻譜與超音波 C-scan 的結果，此超音波 C-scan 圖形與第 500 週次的圖形基本相同，但離圓孔邊緣 1.5mm 的光纖光柵的頻譜則持續出現明顯的變化，換言之 C-scan 對於早期的疲勞破壞偵測不具可靠的靈敏度，但內埋的光纖光柵感測器則相當靈敏，在破壞的極早期即可掌握其出現及發展，另一方面，以 X-ray 放射照相同樣無法發現極早期的疲勞破壞（圖三）

光纖光柵對複材內部疲勞破壞的偵測靈敏度雖高，但卻無法知道何種破壞在發生，後者可透過破壞性的顯微觀察來了解，圖三顯示在圓孔邊緣附近，已出現廣泛的基材裂縫，這些微裂縫導致圓孔附近的應力/應變分佈改變，光纖光柵感受這些改變，所以其頻譜發生複雜的變形與漂移。

疲勞破壞的持續監測

本實驗所選擇的周期負載下，複材試片的疲勞壽命達近百萬週次，所以在後續的頻譜監測上，改採較長的間隔，每一至二萬週次始記錄一次，另因 X-ray 照相對於破壞機制有就佳的解析度，所以每當光纖光柵頻譜出現較為特殊的變化時，疲勞實驗也中斷下來，將試片進行 X-ray 照相檢測，X-ray 照相檢測因牽涉到需滲入對 X-ray 不透明的化學藥品，為免影響後續的疲勞實驗，該試片即不再使用，所以每一階段的疲勞破壞檢測，均從以相同測試條件但不同的試片來進行。

在近百萬週次的疲勞過程中，頻譜的主要變化可區分為四個階段，在一萬週次左右，最靠近圓孔邊緣的第一個光纖光柵頻譜首先出現劈裂的現象 （見圖四，虛線為原來頻譜），頻譜的主峰稍往左邊漂移，另原來單一的主峰在左邊明顯劈裂出一個次峰，另一方面，離圓孔邊緣 3mm 的第二個光柵，其主峰雖沒有漂移，但其左邊也開始有冒出次峰的現象。從光纖光柵頻譜特性考慮，主峰漂移代表光柵所在的應變改變，如漂移往左（波長變小），代表應變降低，如主峰劈裂成次峰，代表沿光柵範圍的應變形成一個分佈梯度，因此，在十萬週次左右光柵頻譜出現的現象，顯示原來較均勻分佈的應變演變成分佈梯度，且此分佈梯度中的應變大多比原來的應變為低，比對 X-ray 照相結果，後者沒有顯示出明顯的破壞情形，但顯微觀察（圖 5）則明確看到基材裂縫，基材裂縫不單存在於 90^{o} 層，而且也有蔓延到 45^{o} 層；基材裂縫的出現，正好可以解釋應變梯度的形成。

第二階段的頻譜變化發生在 230,000 週次，前述的頻譜劈裂及左邊次峰的形成，至此在第二個光纖光柵中已完全出現, 第一與第二光柵的頻譜形狀十分類似, 而 X-ray 照相也顯示出± 45^o 方向的纖維間裂開的情形，證諸圖六的顯微觀察，可以看到纖維間的裂開源自圓孔邊緣。

第三階段發生在 500,000 週次左右，在此一階段，最靠近圓孔的第一個光纖光柵，其頻譜幾乎已沒有主峰，在原來主峰的位置，演變成由一系列小峰，而第二個光柵的頻譜也正朝此方向發展，同時，X-ray 照相（圖四）與顯微觀察（圖六）顯示出 0^o 方向的纖維間裂開的情形。

到了 800,000 週次，第一個光柵頻譜一系列的小峰集中成兩個明顯的主峰，而第二個光柵頻譜的主峰則幾乎崩解成一系列小峰； X-ray 照相與顯微觀察（圖七）均顯示除了 0^o 方向的纖維間裂開的情形更為明顯外，也發生了脫層的現象。

比較 X-ray 與光纖光柵，可以看到在疲勞破壞已較為明顯的階段，X-ray 不單可監測破壞的範圍，而且也在一定程度顯示出破壞的機制，光纖光柵則雖可成功監測破壞的進展，但在沒有事前的實驗校正下無法顯示破壞的機制，不過，與其它非破壞檢測方法也可監控，但光纖光柵可提供即時線上的資訊，不需把停機卸下構件作測量，較為方便。

初步結論

一、 利用雙層纖殼長周期光柵的長周期光柵，可以解決鑲埋後長周期光柵特性消失的問題，另一方面，，雙層纖殼長周期光柵的溫度靈敏度雖較單層纖殼長周期光柵低，但其對溫度及應變敏感度有較為平衡的組合，較不易受到輕微溫度改變而影響應變量測的準確度，而其可以量測的有效溫度範圍也較大。

二、 光纖光柵對於極早期疲勞破壞，有不錯的發現能力，遠比傳統的超音波或 X-ray 方法靈敏。

三、 對於持續發生的疲勞破壞，雖然其它非破壞檢測方法也可監控，但光纖光柵可提供即時線上的資訊，不需把停機卸下構件作測量，較為方便。

計畫進度自評

本計劃原擬的第二年工作主要有三方面：

1. 繼續完成長週期光柵及鑲埋後之長週期光柵之感測特性探討, 包括:尋求克服長週期光柵鑲埋後光柵特性喪失之技術以及在感測應用方面的探討。
2. 探討利用一次於二次布拉格波長來解離/分辨溫度-應變耦合之可行性。
3. 鑲埋式取樣光柵之特性探討。

其中第 1 項工作已成功解決長週期光柵鑲埋後光柵特性喪失的問題，並探討過其對溫度與

應變的靈敏度。第 2 項溫度-應變耦合之解離/分辨，則經購置適當的光源，並采用多種參數進行光纖光柵的製造後，仍無法成功地制作出具有二次布拉格波長的光柵，因此此方向並不可行，至於第 3 項工作，則因原來我們借用制作取樣光柵的中正理工學院的準分子雷射加工設施改裝作特定用途之研究，不能讓我們改變系統光路，而嘗試另借其它兩臺準分子雷射，無法成功制作出堪用的取樣光柵，因此無法進行。應變的措施，為變更原定工作，本計劃原擬的目標為先廣泛比較探討不同的光纖光柵感測器的特性，選定最理想的感測器系統，在下一計劃中始深入進行複合材料與結構的內部破壞監測，為因應部分特殊光柵取得的困難無法克服，故提前將下一步利用鑲埋的光柵深入探討複材破壞監測的研究在本年度進行。

後續工作

將會繼續嘗試取得部分特殊光柵，以便繼續完成原擬定的研究工作，如取得的困難無法克服，則後續的工作也擬相應變更，改為深入探討複材結構內部缺陷發生的診斷，監測與監控，除繼續深入完成目前利用光纖光柵對疲勞破壞的監測，並嘗試擴充至衝擊破壞發生的監控，衝擊破壞的診斷與監測。

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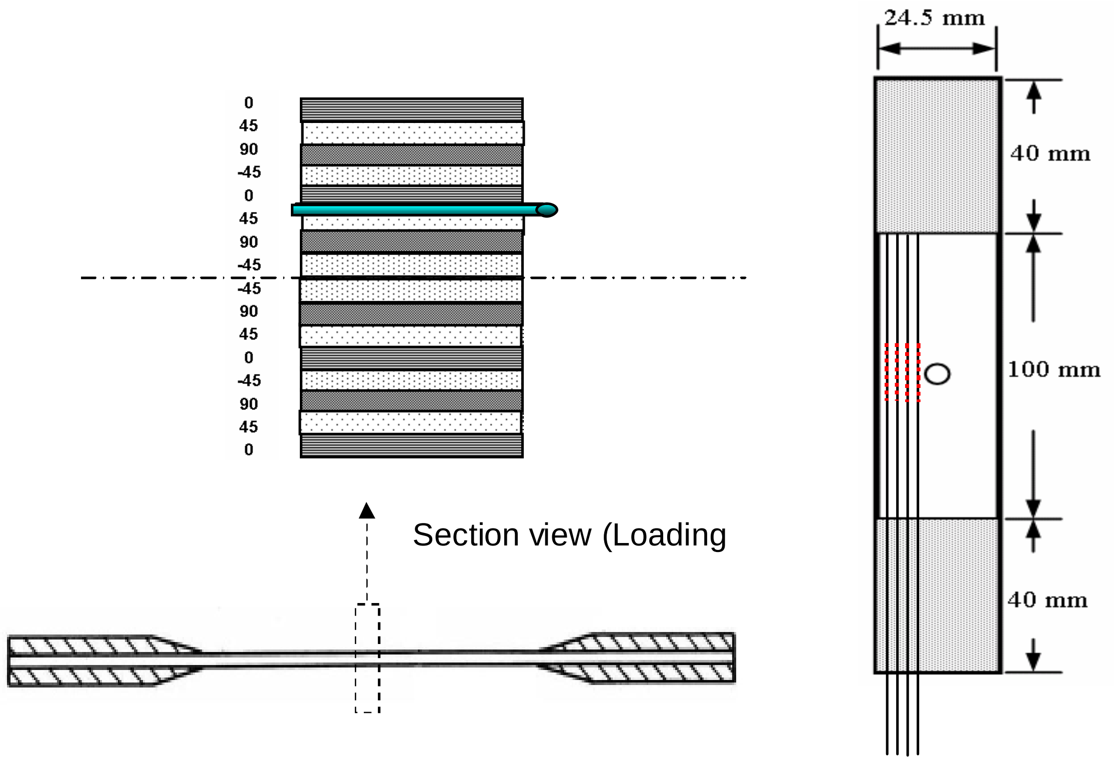
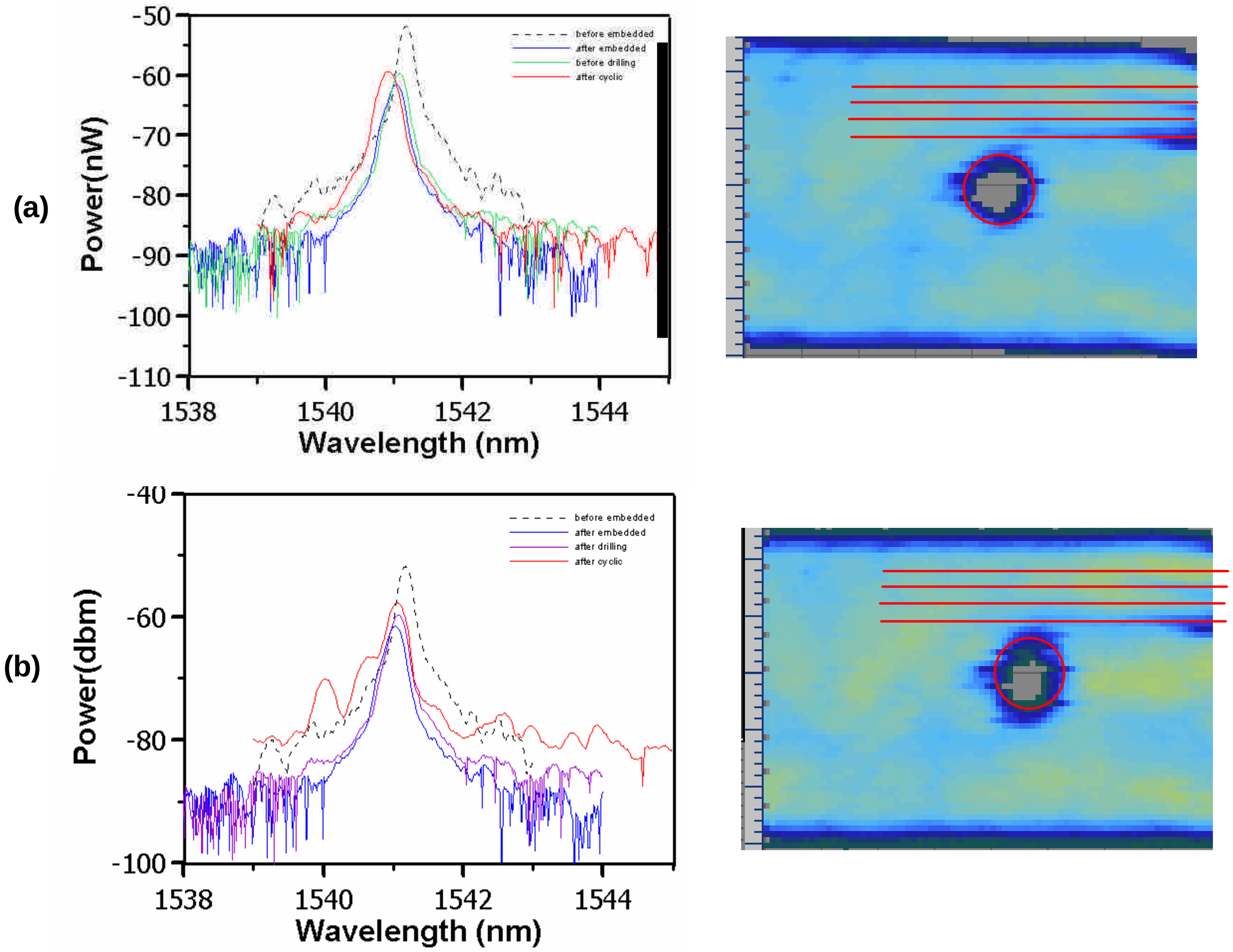
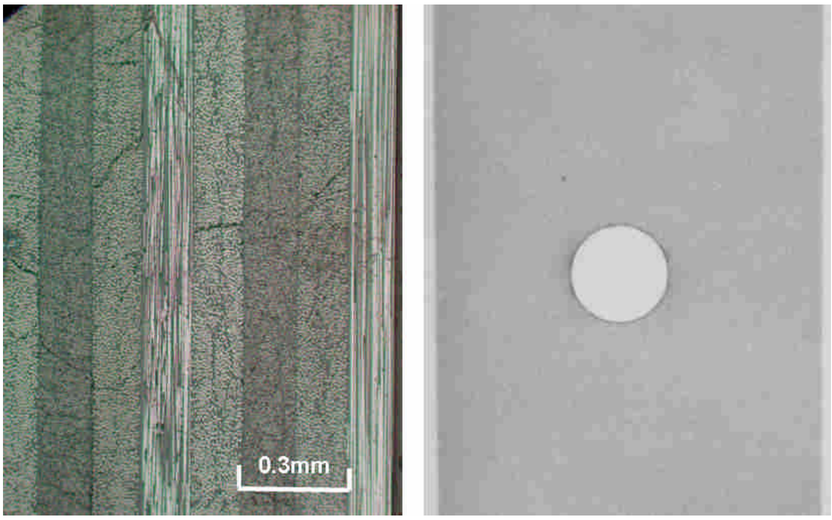


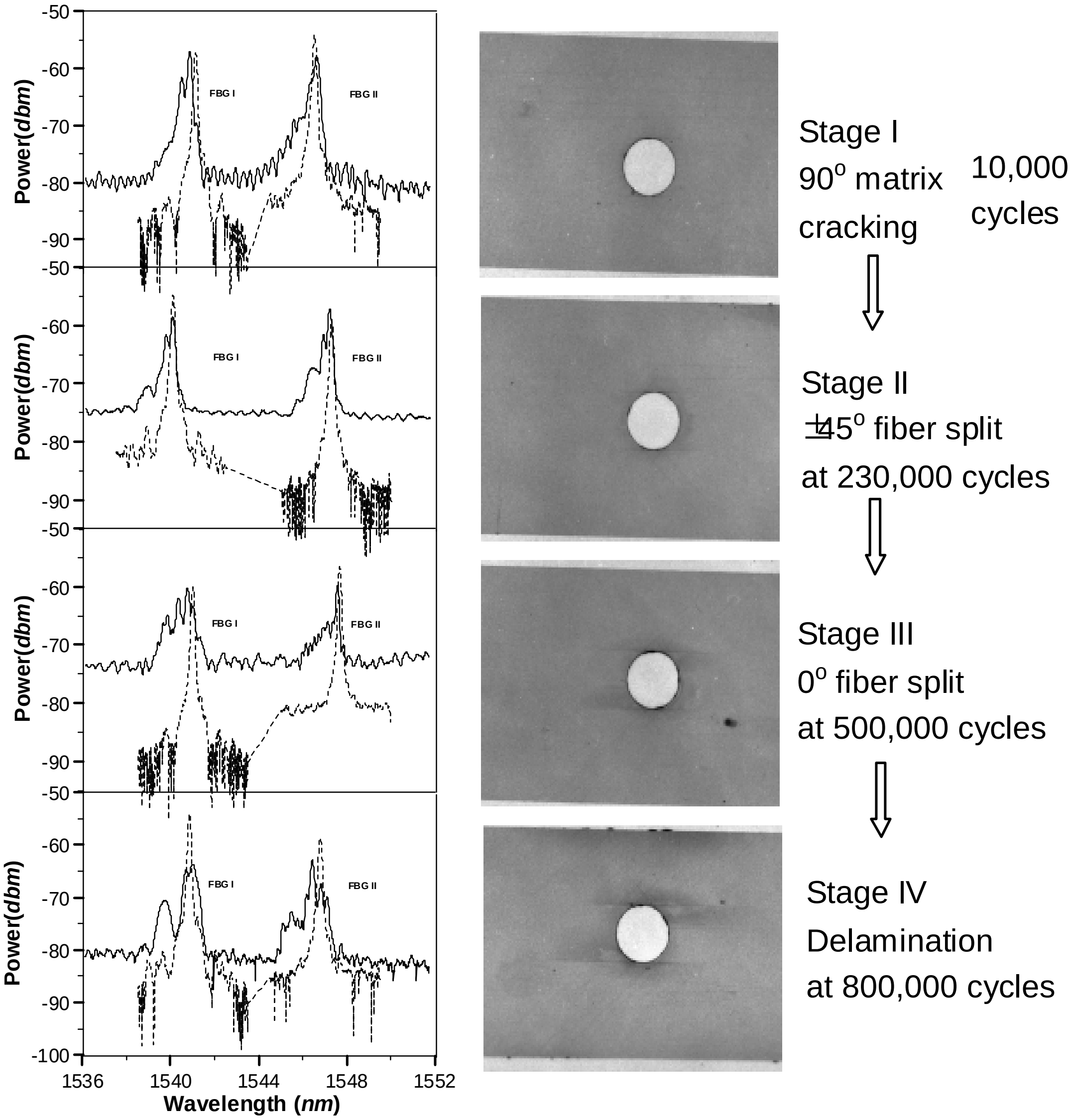
圖一： 複材試片積層方式及光纖光柵感測器布放方式示意圖。



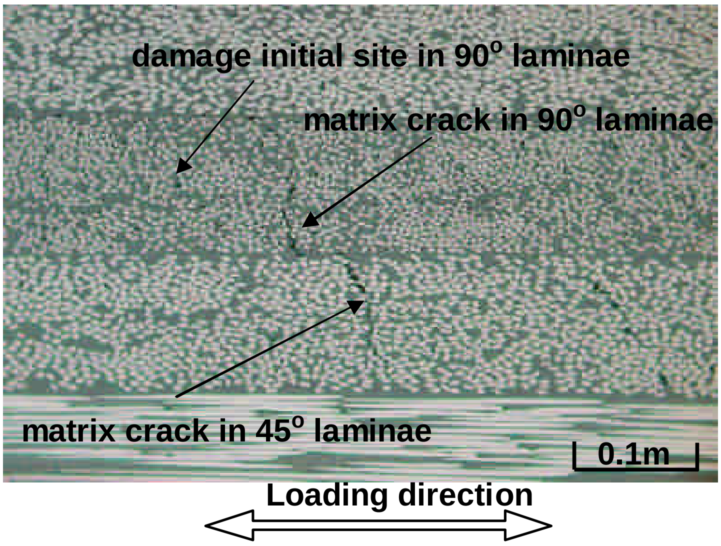
圖二：光纖光柵頻譜與 C-scan 檢測結果比較： (a) 0 週次 (b) 5000 週次。



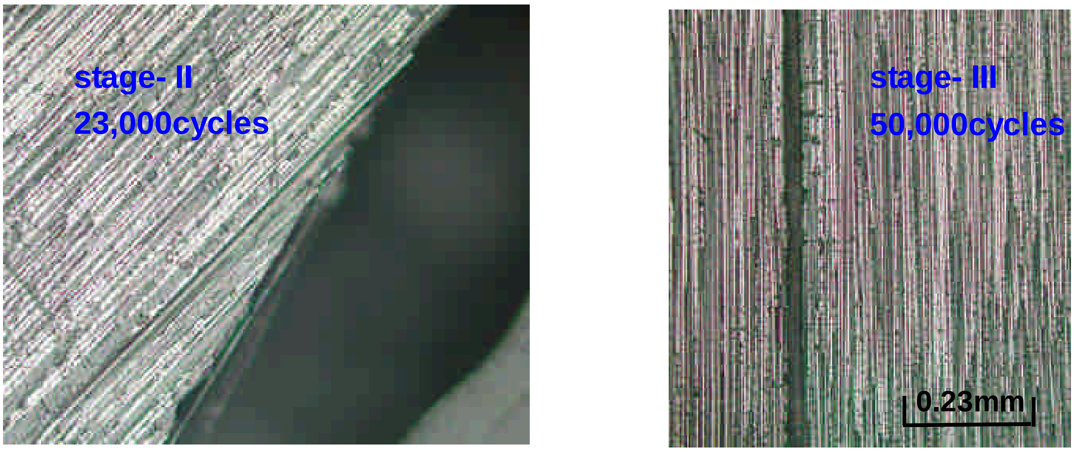
圖三：經受 5000 疲勞週次試片之光學顯微觀察與 X-ray 放射照相比較。



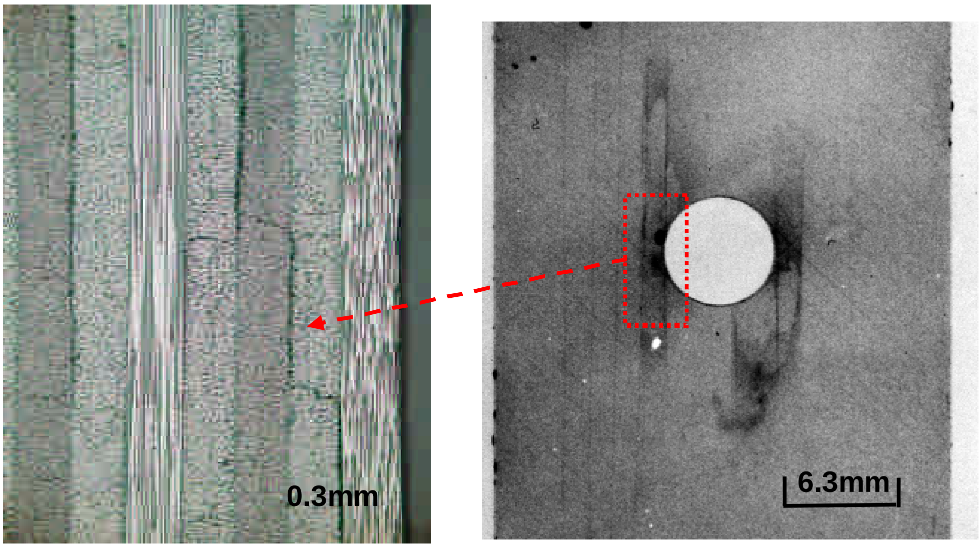
圖四：疲勞破壞四個階段之光纖光柵頻譜變化情形及相應之 X-ray 放射照相比較。



圖五： 10,000 週次疲勞後的破壞顯微觀察。



圖六： 23,000 及 50,000 週次疲勞後的破壞顯微觀察。



圖七： 80,000 週次疲勞後的破壞顯微觀察。

行政院國家科學委員會補助國內專家學者出席國際學術會議報告

96 年　6 月　30 日

報告人姓名	單秋成	服務機構及職稱	國立臺灣大學機械工程學系/研究所教授
會議 時間 會議 地點	2007 年 5 月 22-27 日 中國重慶、南京	本會核定補助文號	NSC95-2212-E-002-021
會議名稱	(中文) 2007 世界智能材料與智能結構論壇 (英文) The World Forum on Smart Materials and Smart Structures Technology 07		
發表論文題目	(中文) 利用光纖光柵進行結構完整性動態監測之系統 (英文) A dynamic strain measurement system using fiber grating sensors and its application in structural health monitoring		

一、參加會議經過

本次會議由中華人民共和國重慶大學、南京大學以及香港理工大學共同主辦，與會者來自多過國家，主辦國中國參加的人數自然是最多，其他還包括美美國，德國，澳洲，意大利，西班牙，波蘭，日本，希臘，南韓，伊朗，埃及，香港，臺灣，中國等。大會的論文分為邀請與會的 Invited Sessions 與自由投稿，我們的論文就屬于前者，是香港理工大學倪一清教授所負責的 “Innovative Sensor and Actuator” session 在籌劃之初來函所邀請而參加的。

大會的論文數目在四百篇以上，所以儘管分五到八個場地同時進行，仍需五天的時間，其中又分前三天在重慶舉行，後二天在南京舉行，場地轉換方面，當地的參加者有自行解決，有利用大會安排的飛機，國外參加者幾乎都利用大會安排的飛機從重慶飛抵南京，整個陣容相當鼎盛，大會的議程見下頁，共有 82 個 sessions， 研討會內容的性質可區分為三大類，為數最多的 sessions 是專業技術層面上有關各種智慧型感測器技術，原理與應用，內容涵蓋各類型創新型的智能感測器及智能致動器技術，結構缺陷定位的技術，土木基建結構完整性的監測，航太結構完整性的監測，結構變形與振動控制等方面，基礎研究與應用研究均具備，而較為偏向應用技術方面。第二類為介紹特定地區的智能材料與智能結構技術的應用，其中包括美國的經驗，歐洲-美國跨國合作的經驗，韓國的經驗，日本的經驗以及大陸的經驗，其中前兩個是以一整個 session 來呈現，其餘則以

Keynote speaker 的方式呈現，第三類也就是最特別的一個 session，是介紹不同地區有關智能材料與智能結構技術的教學經驗，不同單位的教學對象不一，有在校的大學部或研究所學生，也有在職的工程師進行再訓練。

會議地點分重慶與南京，兩地相隔不短距離，這樣的安排較為特殊，可能是要照顧到兩個主要主辦單位（重慶大學與南京航空航天大學）公平性吧。

重慶人口三千多萬，是中國最新但卻是人口最多的一個直轄市，因為才升格沒有很久，基本的公共工程建設比起其他原有的直轄市便相形見拙，加上重慶地形基本為一個建構在山上的城市，道路陡峭而且狹窄，都市規劃看起來比較凌亂，不過，因為升格為直轄市以及發展西部的關系，過去十多年投入大量經費進行基礎工程建設，而民間也經濟活絡，賣房子的廣告到處可見，也到處都可見到大大小小的建築工程在進行中，給人的印象為經濟發展得很蓬勃，此外百貨公司林立，裏面的名牌專柜充斥，其數目與品質的規模，恐怕遠在臺北的百貨公司之上，其金字塔頂層人民的消費力可見一斑。

至於南京，因為是個古都，城市規劃自古就做得不錯，道路寬闊整齊，民房大概在過去數十年有一直在翻新重建，所以整體感覺較為現代化，其市中心的外貌，以不輸臺北東區，而秦淮河一帶，晚上擠得水泄不通，除本地人外，還有不少外地的游客，儘管其對國內的經濟活動大概相當活躍，不過，在國際化方面則似乎仍不發達，此點從搭機返臺的過程中即可見端倪：其國內線班機相當多，機場內人數不少，感覺上遠超過出國時所在的桃園機場第二航站，可是，我們下午兩點的飛機，十二點前到達，卻無法進行報到的手續，原來他的海關要十二點後才開關，一天的國際航班沒有幾班，這點就比不上桃園機場，與香港機場的平均一兩分鐘一班國際線相比，更有霄壤雲泥之別。

World Forum on Smart Materials and Smart Structures Technology

Chongqing & Nanjing, China

May 22-27, 2007

PROGRAM

May 21	May 22	May 23	May 24	May 25	May 26	May 27
Arrival in Chongqing	Chongqing Day 1	Chongqing Day 2	Chongqing Day 3	*Travel to Nanjing*	Nanjing Day 1	Nanjing Day 2

CHONGQING

	Chongqing, May 21, 2007
15:30-17:30	**Registration**
19:00	**Reception**

	Chongqing, May 22, 2007					
7:00-8:00	**Registration**					
8:00-8:30	**Opening Ceremony**					
8:30-10:10	**Keynote Speakers**					
	Prof. Shanglian Huang (China)					
	Dr. Seung-Seok Lee (Korea)					
10:10-10:30	**Coffee Break**					
10:30-12:30	**Parallel Sessions**					
	Invited: Localization of Damage in Structural Systems: Algorithms and Issues	Invited: Application-driven Infrastructure Monitoring in Japan		Invited: Smart Structural Systems Technologies (SST)	Invited: Civil Infrastructure Monitoring and Assessment	
	Session Papers:	Session Papers:		Session Papers:	Session Papers:	
	380	487		435	13	
	381	320		436	404	
	382	488		437	405	
	383	117		438	7	
	384	489		439	406	
	385	198		440	407	
12:30-13:30	**Lunch**					
13:30-15:30	**Parallel Sessions**					
	Localization of Damage in Structural Systems: Algorithms	Electroactive Sensors and Actuators (1)	Innovative Sensing Systems: Fiber Sensors	Smart Materials and Structural Systems	Civil Infrastructure Monitoring and Assessment	Invited: Smart Control Systems Based on MR Fluids
	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:
	103	9	113	214	131	441
	349	251	132	66	143	442
	163	199	256	2	267	443
	250	317	281	142	98	444
	92	178	288	125	119	445
	554		367	548		446
15:30-16:00	**Coffee Break**					
16:00-18:00	**Parallel Sessions**					
	Structural Health Monitoring	Piezoelectric Composite Sensors (1)	Innovative Actuators	Smart Structural Systems and Materials	Innovative Sensing Systems (1)	Magnetorheological Fluids and Dampers (1)
	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:
	154	129	284	315	228	14
	368	136	285	552	263	16
	73	138	293	33	366	46
	55	273	179	34	248	75
	10		37	114	68	286
	6			549	278	551
19:30-21:00	**Night View Tour**					
	Chongqing, May 23, 2007					
7:00-8:00	**Registration**					
8:00-8:30	**NSF Reporting Session**					
8:30-10:10	**Keynote Speakers**					
	Prof. Hoinie (Japan)					
	Kwang J. Kim (USA)					
10:10-10:30	**Coffee Break**					
10:30-12:30	**Parallel Sessions**					

表 Y04

10:30-12:30	Parallel Sessions					
	Invited: Recent Advances in Structural Damage and Fault Detection in the United States	Invited: Model Updating for Civil Applications	Invited: Life-cycle Performance Assessment Based on Structural Health Monitoring	Invited: Novel Technologies and Methods of SHM for Decision Making	Invited: Smart Materials and Intelligent Systems (US-Europe ongoing research cooperation efforts)	Invited: Data-Driven Approaches and Structural Informatics for Next Generation Smart Structures (Data-Driven Approaches)
	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:
	456	490	536	428	83	408
	457	107	537	429	137	409
	458	491	538	430	166	410
	459	492	539	431	542	411
	460	493	540	432	141	412
	461	494	541	433	122	413
12:30-13:30	Lunch					
13:30-15:30	Parallel Sessions					
	Structural Damage and Fault Detection (1)	Smart Control Systems Based on MR Fluids	SHM of Civil Structures	Motion and Vibration Control	Motion and Vibration Control Structures (1)	Invited: Data-Driven Approaches and Structural Informatics for Next Generation Smart Structures (Sensor Informatics)
	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:
	1	90	274	35	219	414
	123	271	308	36	41	543
	348	240	109	304	81	415
	24	53	332	90	253	416
	174	252	290	187	267	417
	333	316	104	66	321	418
15:30-16:00	Coffee Break					
16:00-18:00	Parallel Sessions					
	Structural Damage and Fault Detection (2)	Magnetorheological Fluids and Dampers (2)	Signal Processing for SHM	System Identification and Damage Detection	Motion and Vibration Control Structures (2)	Innovative Sensing systems (2)
	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:
	72	63	354	45	284	372
	225	64	121	144	373	309
	40	104	195	82	118	124
	105	191	165	299	224	22
	201	47	134	295	59	128
	19	112	18	100	238	287
19:00-20:30	Banquet					
	Chongqing, May 24, 2007					
7:00-8:00	Registration					
8:00-8:30	NSF Reporting Session					
8:30-10:10	Keynote Speakers					
	Ming Wang (USA)					
	Education session (Prof. Yunfeng Zhang)					
10:10-10:30	Coffee Break					
10:30-12:30	Parallel Sessions					
	Invited: Transformative Application of Smart Sensor Technology in Health Monitoring	Invited: Innovative Sensors and Actuators	System Identification	Invited: In-situ Materials Monitoring	Invited: Educating Next-Generation Engineers on Smart Structures Technology	Invited: Nano-scale materials for civil infrastructures
	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:
	499	447	32	386	397	531
	500	448	38	387	398	532
	202	205	216	389	399	533
	501	208	311	390	400	167
	544	449	223		401	534
	502	450	260		402	535
					403	
12:30-13:30	Lunch					
13:30-15:30	Parallel Sessions					
	New Sensor Technology for Civil Engineering Structures: Wireless	Piezoelectric Composite Sensors (2)	Analysis and Assessment of Structural Systems	Smart Structural Systems and Materials	Smart Structural Systems	Electroactive Sensors and Actuators (2)
	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:
	377	139	295	371	244	310
	203	326	229	259	277	180
	323	331	77	61	109	303
	369	360	80	44	230	12
	197	292	355		251	39
		243	79		356	
16:00-18:30	Three Gorges Museum Tour					

表 Y04

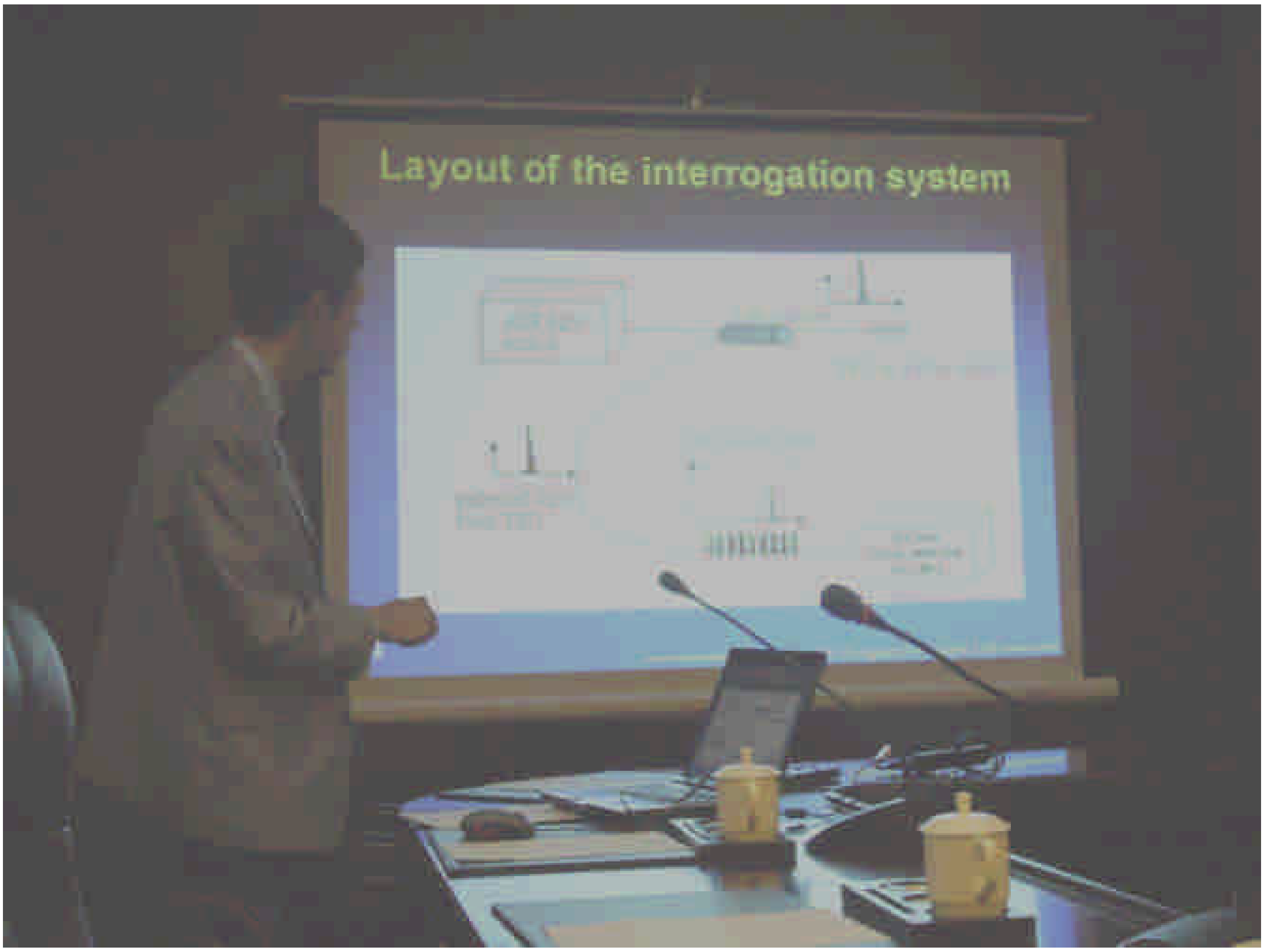
	Nanjing, May 26, 2007							
7:00-8:00	**Registration**							
8:00-8:30	**Opening Ceremony**							
8:30-10:10	**Smart Materials in Action Session**							
10:10-10:30	**Coffee Break**							
10:30-12:30	**Parallel Sessions**							
	Invited: Bio-inspired Structures and Materials (1)	Invited: Damage Detection and Control of Structures	Invited: New Sensor Technology for Civil Engineering Structures	Invited: Functional Materials and Devices For Smart Structures	Invited: Morphing Structures and Systems	Invited: Recent Advances in Aerospace Systems		Invited: Paradigms and Technologies Related to the Engineering and Management of Intelligent Infrastructures and Constructed Systems (1)
	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:		Session Papers:
	474	495	509	482	483	423		515
	475	496	510	483	484	280		516
	476	209	511	484	485	424		517
	477	497	512	485	486	425		518
	394	498	513	486	318	426		519
	478		514	487	319	427		520
12:30-13:30	**Lunch**							
13:30-15:30	**Parallel Sessions**							
	Invited: Bio-inspired Structures and Materials (2)	Localization of Damage in Structural Systems: Algorithms	New Sensor Technology for Civil Engineering Structures	Electroactive Sensors and Actuators (1)	Motion and Vibration Control	Innovative Sensing systems	Magnetorheological Fluids and Dampers (1)	Invited: Paradigms and Technologies Related to the Engineering and Management of Intelligent Infrastructures and Constructed Systems (2)
	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:
	480	279	84	546	247	241	189	521
	481	148	42	547	348	254	190	522
	482	161	274	300	383	221	248	523
	394	189	278	339	346	312	152	524
	553	5	385	352	222	347	239	525
		396	341	227	500	388	301	526
15:30-16:00	**Coffee Break**							
16:00-18:00	**Parallel Sessions**							
	Model Updating and Hybrid Simulation	Structural Damage and Fault Detection	Civil Infrastructure Monitorig and Assessment	Electroactive Sensors and Actuators (2)	Motion and Vibration Control Structures	Innovative Sensing Systems: Fiber Sensors	Magnetorheological Fluids and Dampers (2)	Invited: Paradigms and Technologies Related to the Engineering and Management of Intelligent Infrastructures and Constructed Systems (3)
	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:
	171	57	172	378	8	258	81	527
	115	188	192	204	129	266	71	528
	184	11	234	196	10	217	85	529
	38	220	338	168	181	289	249	530
	382	74	86	186	270	183	370	Panel Disc.
				237	233			Panel Disc.
	Nanjing, May 27, 2007							
7:30-8:30	**Registration**							
8:30-10:10	**Keynote Speakers**							
	Dr. Ohnishi							
	Dr. Jinhao Qiu							
10:10-10:30	**Coffee Break**							
10:30-12:30	**Parallel Sessions**							
	Invited: Developments and Experiments in Biomimetic Robots	Invited: Motion and Vibration Control	Invited: Panel Discussion: Global Collaborations in Smart Structures	Invited: Smart Systems and Mechatronics	Invited: Targeted Energy Transfer and Energy Pumping	Innovative Sensors and Actuators: Shape memory alloys	Invited: Electroactive Polymer Sensors and Actuators	
	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	Session Papers:	
	468	481	Panel Disc.	91	192	52	391	
	469	482	Panel Disc.	503	322	101	392	
	470	483	Panel Disc.	505	419	265	393	
	471	484	Panel Disc.	506	420	82	398	
	472	485	Panel Disc.	507	421	342	396	
	295		Panel Disc.	508	422	283		
12:30-13:30	**Lunch**							
13:30-15:30	**Parallel Sessions**							
	Data-Analysis Methods	Smart Control Systems Based on MR Fluids	Applications of Smart Materials		System Identification	Technologies and Methods of SHM	Piezoelectric Composite Sensors	
	Session Papers:	Session Papers:	Session Papers:		Session Papers:	Session Papers:	Session Papers:	
	306	93	359		302	375	88	
	182	238	352		336	68	275	
	344	170	44		48	340	357	
	390	185	99		337	3	548	
	173	94	176		133	21		
	354	50	297					
15:30	**Closing Ceremony**							
19:00-20:30	**Banquet**							

表 Y04

表 Y04 大會安排往重慶三峽博物館參觀時在博物館對面重慶人民大禮堂合攝

大會安排往重慶三峽博物館參觀時在博物館對面重慶人民大禮堂與筆者學生及中興大學的參加者合影

參觀重慶大學光電所與筆者學生及中興大學的參加者合影



筆者作報告的情形

二、與會心得

參加此會議有幾個較為重要的心得：

（一）　大會在中國大陸舉辦，論文的大宗自然是來自大陸，從其論文的質量，可以看到各大學在對於智能結構方面的研究發展上所獲得的經費比起台灣要龐大得多，主要原因除了因為政府方面對重點學校的研究方面投資不少外，也因為大陸近年經濟起飛，在基礎建設上的投資十分龐大，各地都在競相進行，而學校的研究單位，能主動爭取到不少合作研究計劃，在基礎建設的結構如橋梁，廣播發射塔，大樓等內部建置智能感測器，提供結構完整性的監測診斷，以邀請我們投稿的香港的理工大學倪一清教授所說，近年他們在中國各城市接到為數不少的研究計劃，計劃的方向大致為其基礎工程建設需要研究論證或要進行結構完整性的監測，尤其是後者，最近他們這方面的計劃包括監控香港從機場接市區的捷運有一座跨距世界數一數二的橋梁，下層走捷運，上層為汽車的高速公路，另一個更為大型的計劃為廣州將要興建的世界最高（600 多米）廣播發射塔，由他們設計建構裏面結構完整性監控的智

慧型裝置，後者牽涉的經費相當龐大，反觀我國次與會的幾個學校有關智能結構方面的研究，從政府方面取得的預算基本透過國科會計劃，預算的規模不大，而國內基礎建設有限，也很少想到要引進智能監控，因此，相關的研究都只能在較小的範圍下進行單點突破，在效率與競爭力上無疑是輸人一大截，這實在是值得深憂的。

（二）　除了中國大陸對智能結構展開不少實務的應用外，科技比較進步的歐美地區固不待言，而亞洲方面，日本與韓國也投入不少基礎研究以及結合實務的應用，而且他們都有國家級的研究單位投入專門的研究計劃在智能結構方面，顯然各國都看到此方面的研究最終可以導致相當大的產值與經濟效益。

（三）　有關介紹不同地區有關智能材料與智能結構技術的教學經驗的一個 session，其中提到頗為發人深省的兩點，其一為國外因注意到智能材料與智能結構的重要性，不單在基礎研究，實務研究以及產學合作方面大力投入，在基礎教育以及執業工程師的再教育方面，也投入大量心血，對於一個有經濟潛力的領域，這種完整的由各個層面的切入的方式無疑是十分高明的做法，相當值得我們借鏡；其二為其中一個提供在職工程師再教育的單位對學員所作的問卷調查，提到很多學員再回到學校修習的原因，是他們看到智能結構的潛在經濟效益以及其日漸普遍應用的狀況，深覺不懂此方面的知識，不利於事業的發展，在職者對相關的業界趨勢的嗅覺是最靈敏的，故此二現象也值得我們深思。

三、考察參觀活動(無是項活動者省略)

無。

四、建議

五、攜回資料名稱及內容

大會僅準備了所有論文的摘要的合訂本，至於會議的論文集，因為論文全文至會場時才繳交，並委托一家國外的出版公司印行，至於出版的時間，經向大會主事者詢問，仍沒有明確的答案。

六、附錄: 本此次與會的論文。

A dynamic strain measurement system using fiber grating sensors and its application in structural health monitoring

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ABSTRACT: Fiber Bragg grating (FBG) sensors have found increasing uses in structural applications. Conventional interrogation systems for these sensors are often slow in speed and can only cope with quasi-static signals. A simple, low cost and fast responding interrogation system that makes use of a hybrid fiber Bragg grating-long period fiber grating arrangement to achieve intensity modulation has been developed. The system is capable of measuring dynamic strain variation up to 150 kHz. By means of this dynamic response capability, the system has been successfully applied to detect the occurrence of small missile impact on a metallic plate and a polymeric composite laminate. Comparison of the waveforms recorded from the impact attack on different points of the metal plate suggested that it is possible to locate the position of the impact. On the other hand, by periodic monitoring and comparing the responses of the embedded FBG, it is possible to reveal the occurrence of subsequent internal damage incurred in the composite laminate. These applications have good potential to be developed into full-scale structural health monitoring and diagnosis system.

Keywords: fiber grating sensors, intensity modulation, dynamic strain interrogation, impact monitoring, structural integrity monitoring.

1 INTRODUCTION

Fiber Gratings have found increasing applications as sensors in aerospace, structural, medical and chemical applications for vibration, temperature, strain, impact and general structural health monitoring (Rao 1999; Tomasel et al. 2002; Leng et al. 2002, 2003; Lau et al. 2000). These sensors are light, have small sizes, good sensitivity, good long-term stability, corrosion resistance and are immune to magnetic and electromagnetic interferences. Their small sizes and compatibility with common polymeric materials make them easily embeddable inside a structure without inducing significant weakening of the material. Changes in the physical quantity they monitor are normally reflected as shift in wavelength. Several methods for interrogating such a wavelength shift are currently in use. These include the Fiber Fabry-Pèrot Tunable Filter technology (Kersey et al. 1993), diffraction grating technology such as in optical spectrum analyzer and interferometry (Xu et al. 1993; Rao et al. 1995). These techniques normally involve complex and delicate setup, are expensive and often place unacceptable limits on the dynamic responses. Light intensity detecting techniques have been proposed recently for interrogating Fiber Bragg Gratings (FBG) (Zhang et al. 1998, Fallon et al. 1997a,b, 1998), but demonstration has been limited to the monitoring of static strain or temperature. In the current work, an all fiber interrogating system taking advantage of the edge filtering effect of a LPFG (Zhang et al. 1998) has been employed. The system was originally proposed to interrogate FBG sensors. However, either the FBG or the LPFG in this system may in fact be used as the sensor for physical quantities.

2 EXPERIMENTS

2.1 *Operation Mechanism of the interrogation system*

Schematic setup of the current interrogation system is shown in fig.1. The FBG acts as an alternative fiber mirror. When the reflected light is coupled into the LPFG, the later will act as an edge filter. The sensitivity of signal detection and the dynamic range limits can be controlled by carefully matching the Bragg wavelength of the FBG with the resonance wavelength of the LPFG. Depending on the relative positions of these two wavelengths, the amount of energy coming through the LPFG varies. Either the FBG or the LPFG can be used as the physical quantity sensor. If the FBG is used as the sensor and the LPFG is kept in a fixed condition, the reflected Bragg wavelength peak will shift as the quantity to be monitored changes. On passing through the LPFG edge filter, the resulting light energy changes according the Bragg wavelength. The energy is converted into a proportionate voltage by an InGaAs photodetector circuitry.

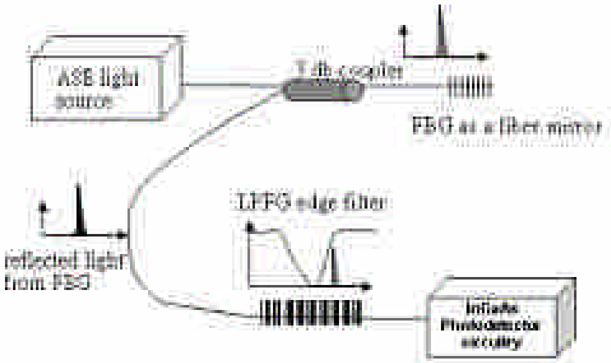

Figure 1 Schematics of the hybrid FBG-LPFG intensity modulation system for interrogation of wavelength shift.

2.2 *Fiber grating fabrication*

The FBGs and LPFG were fabricated by side writing on single mode photosensitive fibers. The reflectivity of the FBG was about 95%, and the peak wavelength was about 1552nm. The characteristic dip spectrum of the LPFG has a center wavelength of about 1540nm and the dip loss was about 10dbm.

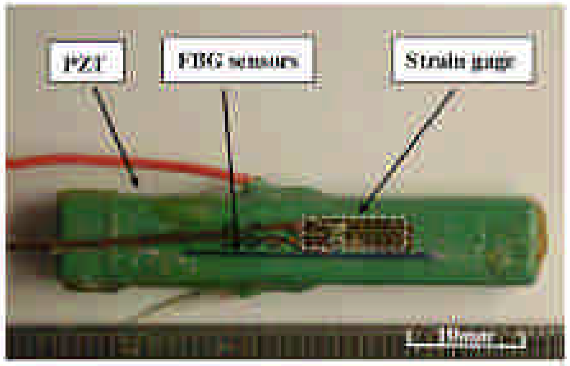

Figure 2 The FBG and strain gage on the PZT actuator.

2.3 *Dynamic Strain measurement applications*

The capability of the system to measure high frequency strain variations was first demonstrated by sticking the FBG onto a multi-layer ceramic piezoelectric actuator. A strain gage was also stuck on the other face of the actuator for comparison purpose (Fig.2). The actuator was driven by a sinusoidal waveform that varied between 0-80V at different frequencies.

The system has also been applied to monitor the occurrence and responses to low energy impact on an aluminum alloy plate and a carbon fiber/Epoxy composite laminate by small missile impact. Square plates of 33cm×27.5cm and 20cm×20cm were respectively employed in aluminum plate and laminate. The FBG was stuck on the surface of the aluminum plate. Placement of the FBG sensor and the related nomenclatures were illustrated in Fig.3. The composite plate was a 8 layer quasi-isotropic laminate with the lay-up sequence $[90^{\circ}/\pm45^{\circ}/0^{\circ}]$s and the FBG was embedded between two middle 0° layers. Impact was brought about by dropping a 68.8g blunt-headed hammer from a height of 12cm at various (r,θ) locations. Signal output was recorded by a high speed digital storage scope for further analysis.

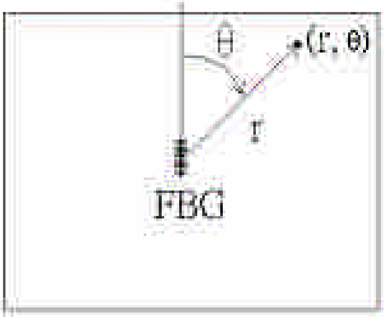

Figure 3 Placement of the FBG on the plate and the orientation angle θ.

3 RESULTS AND DISCUSSION

3.1 *High frequency periodic strain monitoring*

The piezoelectric (PZT) actuator was capable of high frequency straining but the strain range was limited and was frequency dependent. Fig. 4 shows the longitudinal displacement amplitude with frequency of the PZT actuator measured by a laser Doppler vibrometer (LDV) while it was driven by a 0 to 80V sinusoidal waveform.

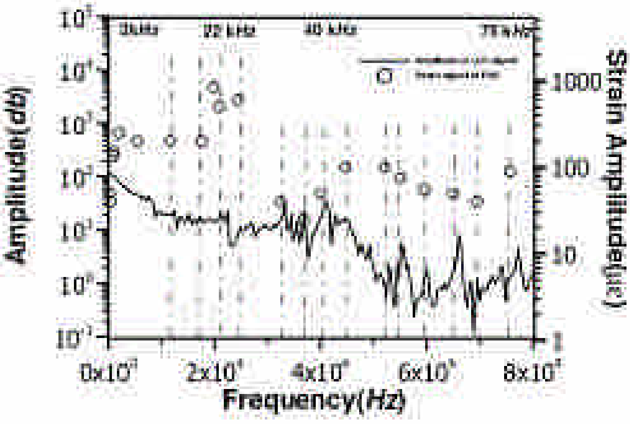

Figure 4 Longitudinal displacement amplitude measured by Laser Doppler Vibometer and strain amplitude measured by FBG when the PZT actuator was driven at different frequencies

During measurement with the FBG, we scanned through the frequency spectrum manually. At most of the frequencies, no signal was obtained. Signals are only measured at a number of specific frequencies and so the FBG results are discrete. To facilitate comparison, vertical lines have been added in Fig.4 to show the correspondence between a specific frequency which the FBG recorded response and the resonance frequencies obtained by a continuous scanning by the LDV.

At a driving frequency below 1 kHz, the output from the current system agrees with that from the strain gage. Above 2 kHz, the strain gage signal becomes attenuated heavily as it is approaching the dynamic response limit (4 kHz) of the strain gage amplifier. The strain gage signal stopped to be meaningful as the small strain output (a few microstrains) was masked by noise. The current system continued to record output with diminishing amplitude and the noise level corresponds to 1.5 με. When the recorded signal amplitude was smaller than 3με, it became overwhelmed by noise. However, a scanning through different frequencies showed that near and at some resonance frequencies (peaks in Fig. 4), the recorded signals became distinct and showed large amplitude again. The strain amplitudes recorded are also shown in Fig. 4 for comparison. Typical signals recorded by the strain gage and the current system at one of these resonance frequencies (22 kHz) and at 2 kHz are shown in Fig. 5.

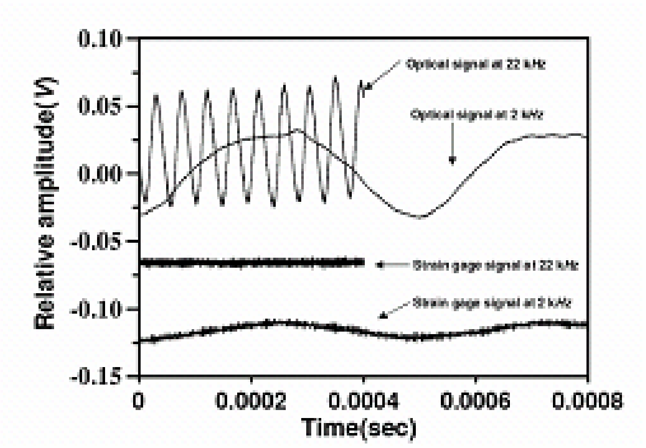

Fig. 5 Comparison of output signals from strain gage and the hybrid FBG-LPFG Intensity modulation system under high frequency ,strain variation.

Fig. 6 shows signals typically recorded by the current system at some of the resonance frequencies up to 75 kHz. Signal up to 150 kHz has been measured with this system. The frequencies of the signals agreed with the corresponding driving frequencies. Moreover, perturbing the driving frequency near these resonance conditions induced corresponding variations in the signal frequency and amplitude. Hence, the measured output was reflecting the deformation of the PZT. At high frequencies, the strain amplitudes recorded by the FBG do not exactly match the longitudinal displacements measured by the LDV. It is reasoned that different resonance frequencies are associated with different modes of deformation. Although the end-to-end longitudinal displacement at the resonance frequencies are small, the out-of-plane deformation along the PZT may cause significant straining of the FBG sensor and give the observed outputs. It can be concluded that the current system has an acceptable dynamic response at least up to 150 kHz.

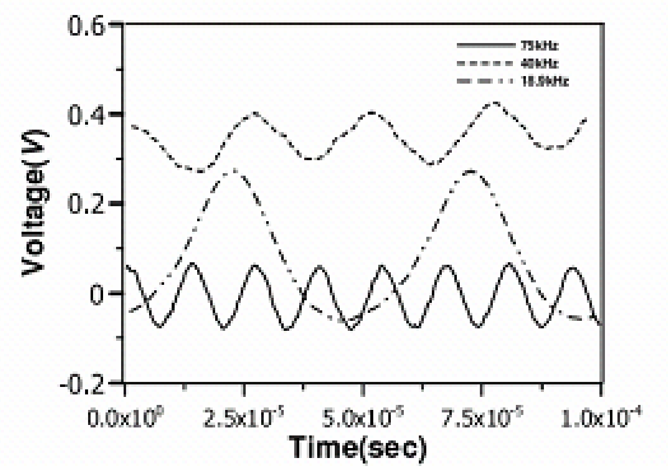

Figure 6 The strain signal monitored by the FBG using the intensity modulation system when the PZT was driven at various resonance frequencies.

3.2 *Small missile impact monitoring in aluminum plate*

Fig. 7 shows the waveform signal recorded from the FBG when impacts were made along the line $\theta = 0^{\circ}$ at a various r's. The waveform pattern gradually changes with the impact distance from the FBG. The evolution in waveform pattern is particularly clear if the first valley and peak are considered. When the impact signal was just received, there is initially a small valley in the waveform. This is followed by a large peak. As r increases, the depth and width of the initial valley increase while that of the following peak decrease. Subsequently, the peak does not decrease regularly any more with the increase of impact distance from $r \geq 6cm$. Such a phenonmenon may be due to the boundary effect as the impact spot is getting near to the clamped edge of the plate. Work on a much larger plate is underway to check this. Similar evolution in the waveforms occurred for θ=22.5° and 45°. For θ=67.5° there is no small valley before the first peak ① (see Fig.8). Instead, the second peak ② becomes more distinct. As r increases, the ratio of the first peak① to the second peak② will decrease. For θ= 90°, a deep valley occurs initially with no obvious single peak following.

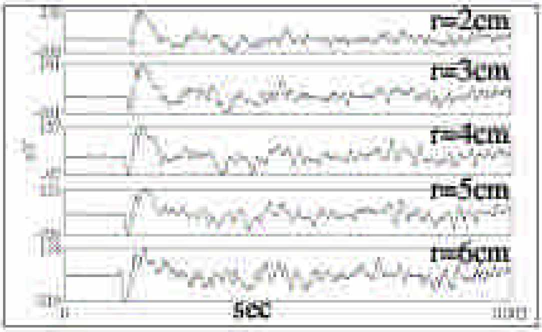

Figure 7 Waveforms from different r's at θ=0°

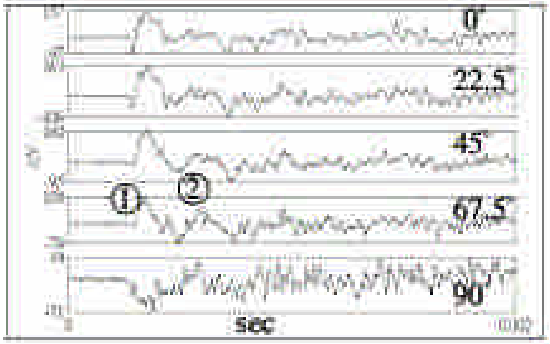

Figure 8 Waveforms from different θ at r=4cm

The differences in the waveform information suggest that one may locate the position of further missile impacts by matching and comparing the waveform with a set of pre-calibrated data. In order to facilitate quantitative prediction of the location of an unknown impact, the above waveform details are summarized in terms of peak amplitude against valley amplitude for different θ and r as shown in Fig.9. The data labeled P1 and P2 are included in this figure and the next to avoid redundancy and will be discussed later. It can be seen that by plotting the amplitude of the first valley and peak of an impact signal on Fig.9, the approximate θ of the impact location relative to the FBG can be found. Fig.10 plots the centroidal y coordinates of the first 0.0004sec. of the waveform against r. The distance of the impact location from the FBG may be deduced from the centroidal position of the waveform shape. A number of impact with randomly chosen positions have been made. Two typical cases, P1 and P2, are included here to demonstrate how the method works. The impact P1 was located at a θ between 0° and 22.5° and a distance r between 2cm and 3cm.The impact P2 was located at a θ between 67.5° and 90° and a distance r between 4cm and 5cm. The corresponding waveform data were quantified and plotted on Figs. 9 and 10. By observing Fig.9, one can judge P1 and P2 were respectively at $0° < \theta < 22.5°$ and $67.5° < \theta < 90°$. Their centroidal y-coordinate levels are marked as dotted horizontal lines in Fig.10. That of P1 suggests the impact occurred between r=2cm and r=3cm. The level of P2 lies between the points for θ = 67.5° and 90°. It is obvious that we need more calibration points between these two angles for a more comprehensive estimation of impact location.

The above results are derived from a single sensor. If more sensors are used, the redundancy of information should allow the location to be predicted more accurately. With three or more sensors, conventional triangularization technique can also locate the impact position by making use of the difference in the times of arrival of the signals. However, strict synchronization of the different sensors is needed in this technique. In the current work, such stringent requirement is not necessary and the equipment cost can be much lowered.

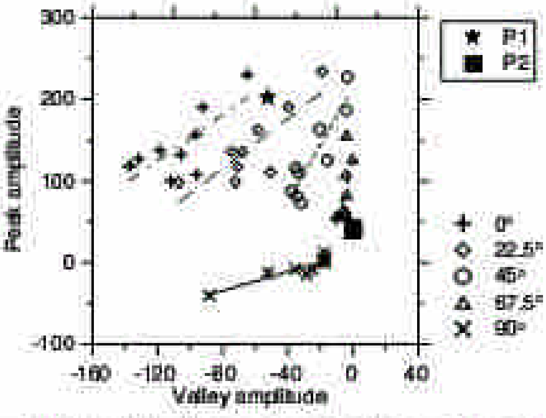

Figure 9 Quantitatively representation of waveforms at θ=0 to 90° and for various r's.

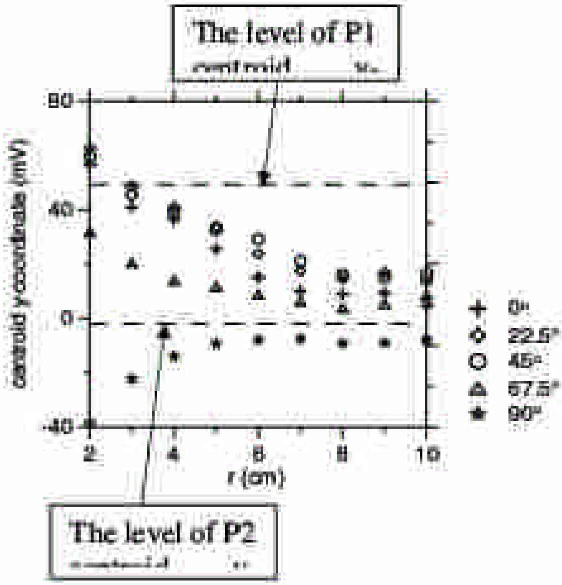

Figure 10 Centroidal y-coordinate of first 0.0004sec of the waveform for different r's.

3.3 *Diagnosis of impact damage in composite laminate*

In this part, the small missile impact is employed as a diagnosis tool. Fig. 11 shows the ultrasonic C-scan image of a composite laminate. An internal impact damage was deliberately made on the laminate at around (r,θ). Before and after the generation of this damage, small missile impact at different locations was carried out and the signals picked up by the FBG were recorded. Fig.12 compares a typical pair of waveform obtained by impacting on (3cm, 0°). The initial valleys and peaks are roughly the same before and after the incurrence of internal damage (Fig.12). Differences begin to emerge at 0.006sec. after the initial signal was received. No simple rules can be generalized for such differences in the time domain. On the other hand, a fast Fourier transform of the waveform showed a shift in each of the peak frequencies to the left occurred (Fig.13). This frequency shift occurred no matter where the diagnostic impact was made. This phenomenon is considered useful for helping to diagnose whether internal damage has been incurred in a composite structure.

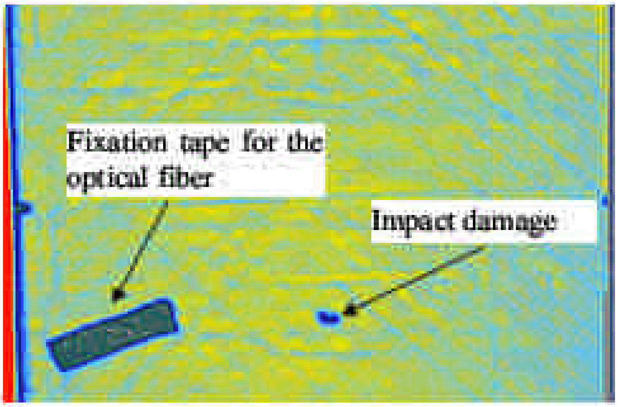

Figure 11 The ultrasonic C-scan image of a composite laminate.

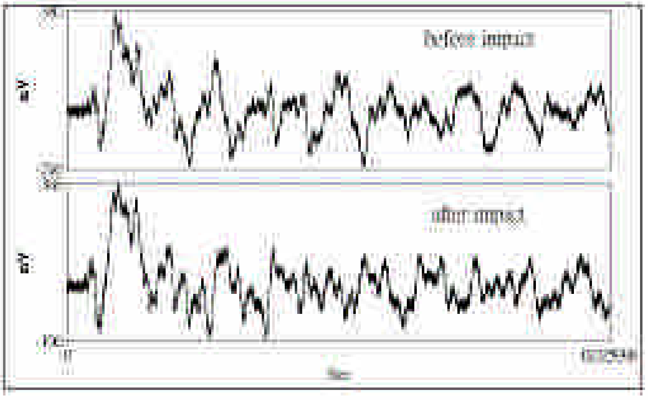

Figure12 Waveforms before and after the occurrence of impact at (3cm,0°).

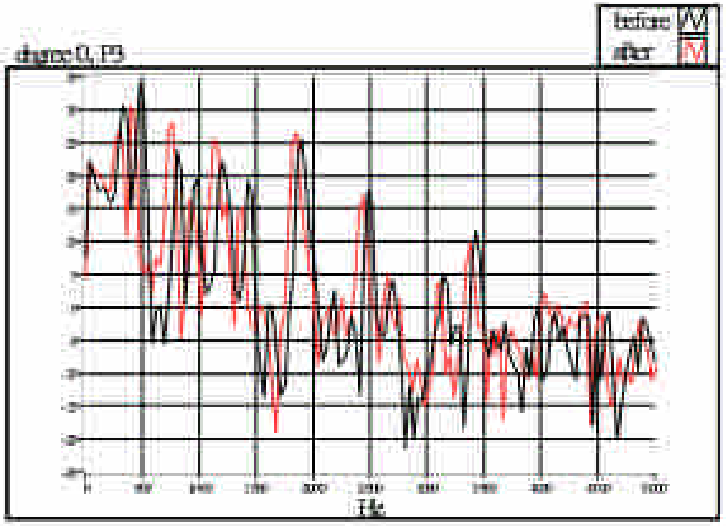

Figure13 Fast fourier transform of the waveform at (3cm,0°).

4 CONCLUSIONS

A low cost and fast responding interrogation system for FBG based on intensity modulation has been developed. The system is capable of measuring dynamic strain variation up to 150 kHz. By using this system, it has been demonstrated the detection and location of small missile impact on a metallic plate can be achieved. Moreover, diagnosis of occurrence of internal damage in a composite laminate can also be made.

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