様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　元 年　 ５ 月 ２８ 日現在

機関番号：１２６０１
研究種目：基盤研究(S)
研究期間：2014～2018
課題番号：２６２２０９１２

研究課題名（和文）光ファイバライフサイクルモニタリング援用革新複合材構造の知的ものづくり科学の構築

研究課題名（英文）Intelligent Manufacturing Science of Innovative Composite Structures Based on Optical-Fiber Life Cycle Monitoring

研究代表者
武田　展雄（Takeda, Nobuo）

東京大学・大学院新領域創成科学研究科・客員連携研究員

研究者番号：１０１７１６４６

交付決定額（研究期間全体）：（直接経費）　 122,800,000円

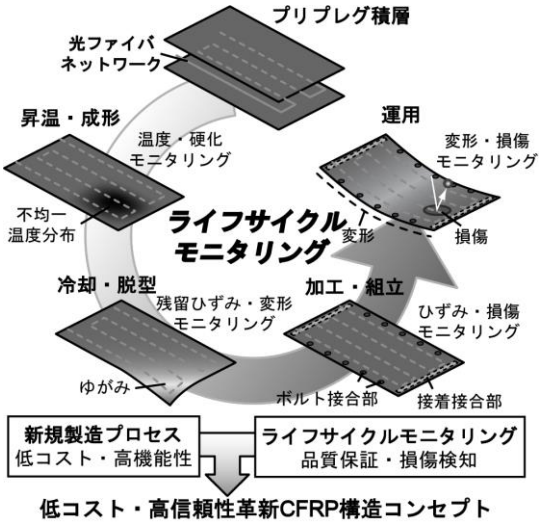
研究成果の概要（和文）：　光ファイバ温度・ひずみ同時計測技術を、炭素繊維強化プラスチック（CFRP）の新規成形プロセスに適用可能なレベルまで向上させ、CFRPの成形、加工、組立、運用に渡るライフサイクルモニタリング技術として提案し、CFRPの品質保証・保守技術としての有用性を実証した。まず、埋め込み光ファイバ援用CFRP成形中その場物性評価基盤技術を構築し、従来では不可能であった成形途中の物性値の時間的変化を測定し、実用的な成形モデリングを行った。次に、脱オートクレーブ・低圧成形CFRP、熱可塑CFRP、CFRP二次接着接合構造、複雑形状CFRP構造等に適用するとともに、実用模擬CFRP構造レベルでの実証に成功した。

研究成果の学術的意義や社会的意義
　CFRPは主要一次構造部材にも適用され、かつ日本の製造技術が強い。しかし、成形・組立などの製造上の問題および損傷後強度保証の難しさがあり、従来金属製航空機と比較して製造コストが高くまた十分な軽量化にも至っていない。
　本研究では、ライフサイクルモニタリングによる構造高信頼化技術と，製造技術に課題はあるものの低コスト・高機能性のポテンシャルを有する新規CFRP製造プロセスを融合させる「複合材構造の知的ものづくり科学」を構築することで初めて可能になる、革新CFRP構造コンセプトを世界に先駆けて提案・実証することを目的とした。日本独自のもので、かつ学術的価値・優位性は高く評価されている。

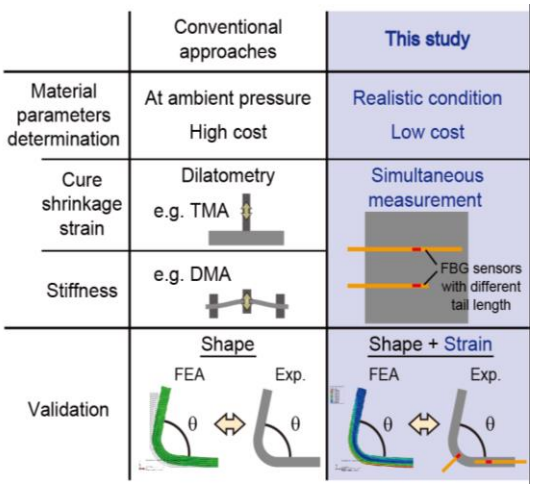
研究成果の概要（英文）：Optical fiber based simultaneous strain and temperature measurement technology was extended to cover the process monitoring of novel carbon fiber reinforced plastics (CFRP). We proposed "life cycle monitoring method" to monitor internal strains throughout the material life from processing, manufacturing, assembly, to operation. We also demonstrated the practical validity of this method for excellent quality assurance and maintenance of CFRP. First we developed a in-process internal strain monitoring system during practical CFRP processing using embedded optical fiber sensors, and internal strain/property change was successfully obtained for the first time.
 This in-process monitoring system was also used to characterize some novel CFRP, such as out-of-autoclave low-pressure CFRP processing, thermoplastic CFRP, secondary bonding CFRP structures and complex shaped CFRP structures. Finally the system was used for prototype aerospace CFRP structures to demonstrate the practical validity.

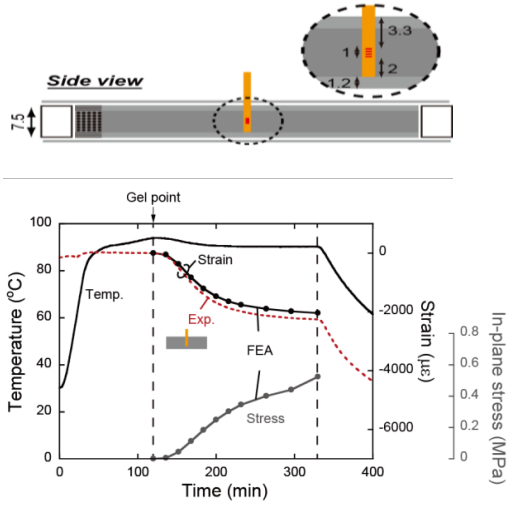
研究分野：複合材料工学

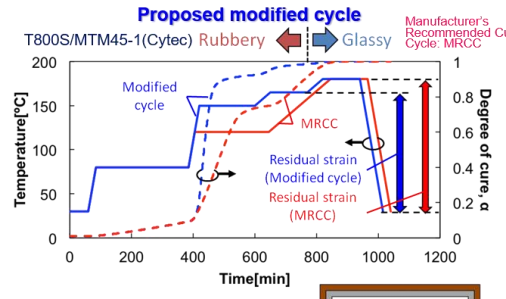
キーワード：複合材料　CFRP　光ファイバセンサ　成形プロセス　モニタリング　品質保証

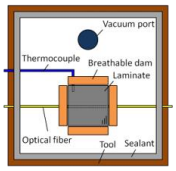


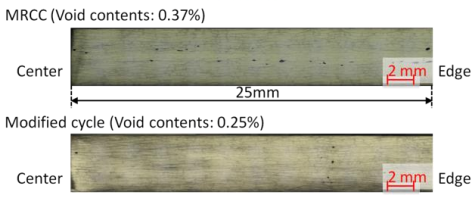
低コスト・高信頼性革新CFRP構造コンセプト

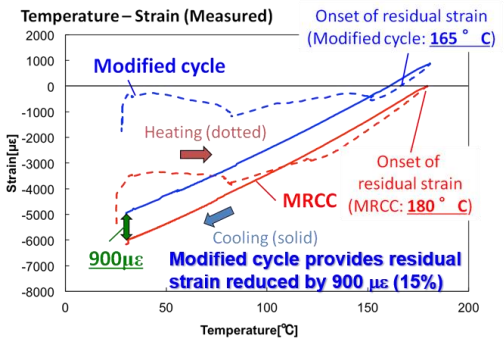


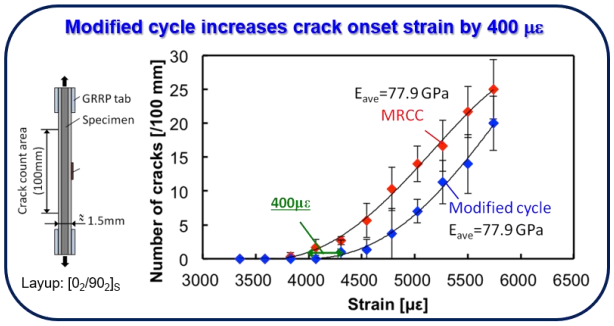


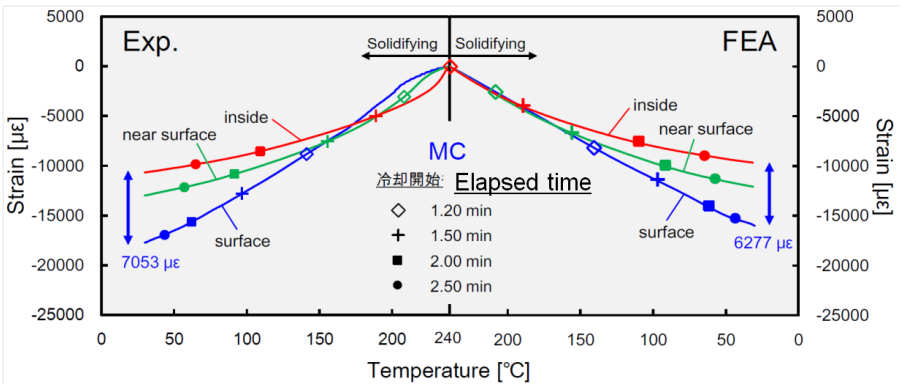

Proposed modified cycle
T800S/MTM45-1(Cytec) Rubbery
Glassy
Manufacturer's Recommended Cure Cycle: MRCC
Modified cycle
MRCC
Residual strain (Modified cycle)
Residual strain (MRCC)
Temperature[°C]
Degree of cure, α
Time[min]

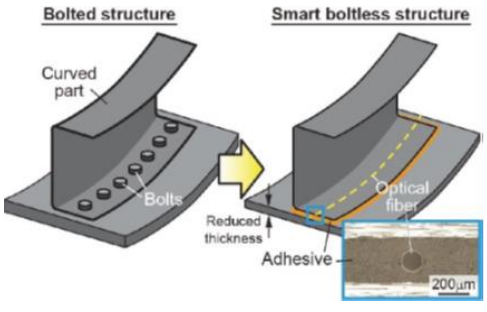

Vacuum port
Thermocouple
Breathable dam
Laminate
Optical fiber
Tool
Sealant

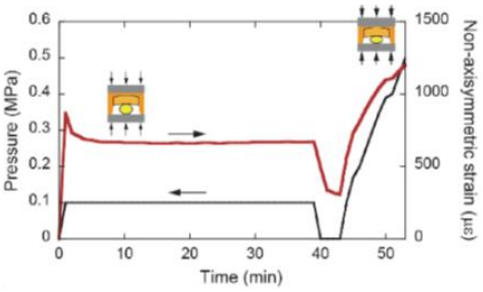

Void contents
MRCC (Void contents: 0.37%)
Center
2 mm
Edge
25mm
Modified cycle (Void contents: 0.25%)
Center
2 mm
Edge

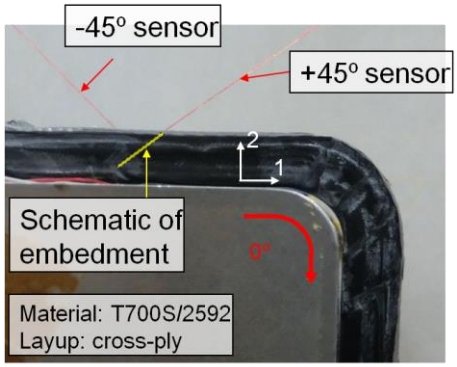

Temperature – Strain (Measured)
Onset of residual strain (Modified cycle: 165 °C)
Modified cycle
Heating (dotted)
Onset of residual strain (MRCC: 180 °C)
MRCC
Cooling (solid)
900με
Modified cycle provides residual strain reduced by 900 με (15%)
Strain[με]
Temperature[°C]

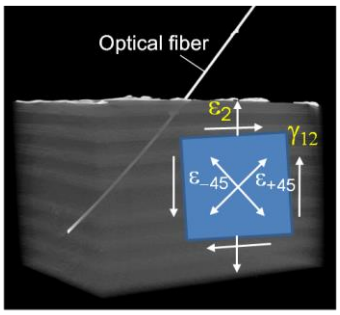

Modified cycle increases crack onset strain by 400 με
GRRP tab
Specimen
Crack count area (100mm)
1.5mm
Layup: [0₂/90₂]S
Number of cracks [/100 mm]
E_ave=77.9 GPa
MRCC
400με
Modified cycle
E_ave=77.9 GPa
Strain [με]


Exp.
FEA
Solidifying
Solidifying
inside
near surface
surface
MC
冷却開始: Elapsed time
1.20 min
1.50 min
2.00 min
2.50 min
7053 με
6277 με
Strain [με]
Temperature [°C]
surface
near surface
inside
Solid
Melting
Solid

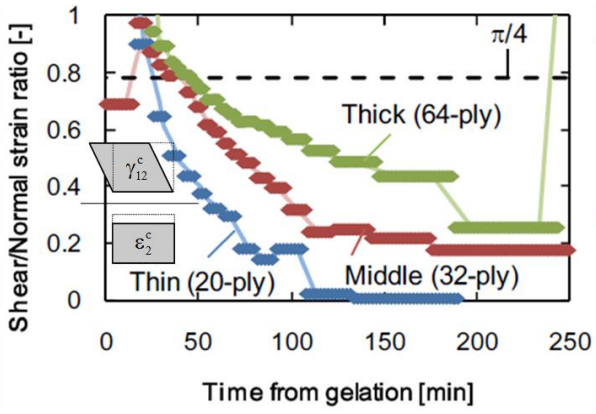

Bolted structure
Smart boltless structure
Curved part
Bolts
Reduced thickness
Adhesive
Optical fiber
200μm

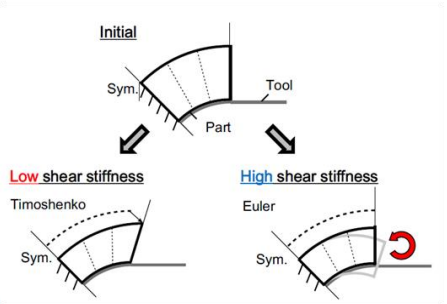

Pressure (MPa)
Non-axisymmetric strain (με)
Time (min)

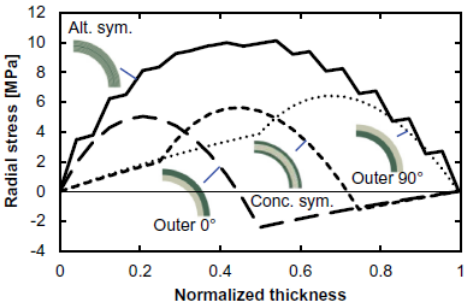

-45° sensor
+45° sensor
2
1
Schematic of embedment
0°
Material: T700S/2592
Layup: cross-ply

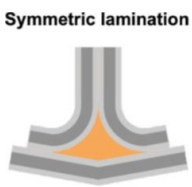

Optical fiber
ε_2
γ_{12}
ε_{-45}
ε_{+45}

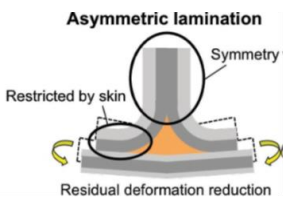
3次元X線CT像

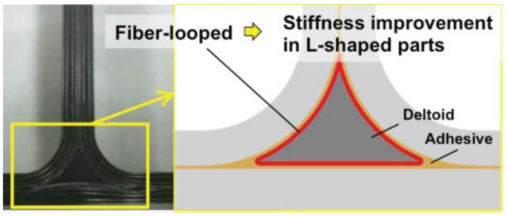

Shear/Normal strain ratio [-]
Time from gelation [min]
π/4
Thick (64-ply)
Middle (32-ply)
Thin (20-ply)
γ_{12}^c
ε_2^c

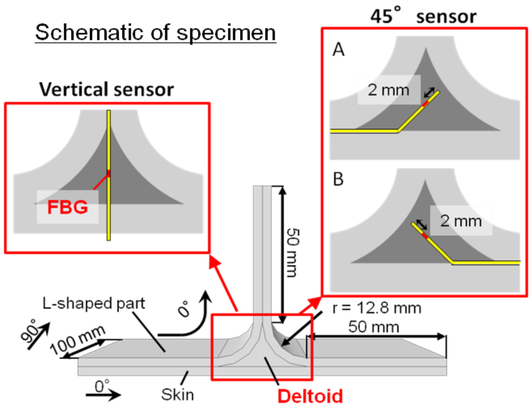

Initial
Sym.
Tool
Part
Low shear stiffness
Timoshenko
Sym.
High shear stiffness
Euler
Sym.

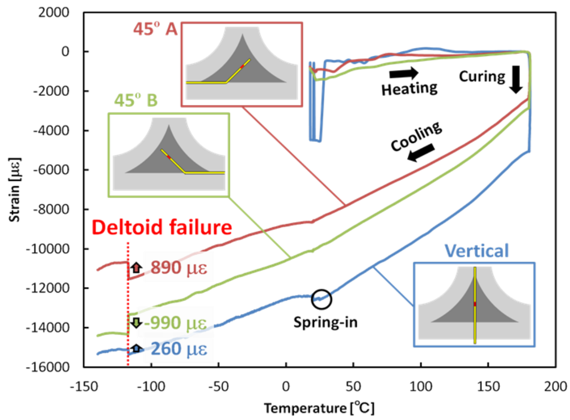

Alt. sym.
Outer 90°
Conc. sym.
Outer 0°
Radial stress [MPa]
Normalized thickness


Symmetric lamination


Asymmetric lamination
Symmetry
Restricted by skin
Residual deformation reduction


Fiber-looped
Stiffness improvement in L-shaped parts
Deltoid
Adhesive





CFRP T-joint Deltoid

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1. , , , , "6 L " CFRP 4B gg$\ g8j " , Vol. 45, No. 2, 2019, pp. 43-51. & 1w

2. T. Tsukada, S.Minakuchi, and N. Takeda, "Identification of Process-Induced Residual Stress/Strain Distribution in Thick Thermoplastic Composites Based on In-Situ Strain Monitoring Using Optical Fiber Sensors", Journal of Composite Materials, in press 2019, DOI:10.1177/0021998319837199. & 1w

3. T. Tsukada, S. Minakuchi and N. Takeda, "Assessing Residual Stress Redistribution During Annealing in Thick Thermoplastic Composites Using Optical Fiber Sensors", Journal of Thermoplastic Composite Materials, Vol. 1, No. 16, 2019, DOI:10.1177/0892705718804580. & 1w

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5. K. Takagaki, S. Minakuchi and N. Takeda, " Process-Induced Strain and Distortion in Curved Composites. Part I: Development of Fiber-Optic Strain Monitoring Technique and Analytical Methods", Composites, Part A, Vol. 103, 2017, pp. 236-251. https://doi.org/10.1016/j.compositesa.2017.09.020. & 1w

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9. J. T. Siivola, S. Minakuchi, T. Mizutani and N. Takeda, "Evaluation of Damage Detectability in Practical Sandwich Structure Application Conditions Using Distributed Fiber Optic Sensor", Structural Health Monitoring, Vol. 15, No. 1, 2016, pp. 3-20. doi:10.1177/1475921715620002& 1w

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11. S. Minakuchi, K. Uhira, Y. Terada, N. Takeda, N. Saito and T. Shimizu, "Quality Control of Composite Bonded Joints Using Fiber-Optic-Based Process Monitoring", SAMPE Journal, Vol. 51. No. 1, January/February, 2015, pp. 44-54. & 1w

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1. Ply Curving Termination /D 10 G1 (JCCM-10) 2019 3/6-3/81n No. 1A-17.

2. N. Takeda, "Integrated In-Process Monitoring of High-Rate Production CFRP Structures for Material Quality Assurance", ASC 33rd Annual Technical Conference & 18th US-Japan

Conference on Composite Materials, Sept. 24-26, 2018, Seattle, USA, Paper No. PL-B. (Plenary)

3. N. Takeda, "In-Process Monitoring of Advanced Composites for Material Quality Assurance", 11th Asian-Australasian Conference on Composite Materials (ACCM11), July 29-Aug.1, 2018, Cairns, Australia, Paper No. PL-1. (Plenary)
4. N. Takeda, "In-Process Monitoring and Quality Assurance of Aerospace Composites", 18th European Conference on Composite Materials (ECCM18), June 25, 2018, Athens, Greece. (Keynote)
5. N. Takeda, S. Minakuchi, "Intelligent In-situ Process Monitoring and Quality Assessment of Aerospace Composite Structures", Proc. CAMX (The Composites and Advanced Materials Expo), Dec. 11-14, 2017, Orlando, USA.& Plenary≯
6. N. Takeda and S. Minakuchi, "Optical Fiber Sensor Based Life Cycle Monitoring and Quality Assessment of Carbon Fiber Reinforced Polymer Matrix Composite Structures," 25th Int. Conf. Optical Fiber Sensors (OFS-25), April 24-28, 2017, Jeju, Korea, Paper No. 10323-576 (1n)

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