Research Executive Agency

PEOPLE
MARIE CURIE ACTIONS

Final Technical Report
(Period covered: 01st August 2013 to 31st July 2015)

Intra-European Fellowships (IEF)
FP7-PEOPLE-2012-IEF

Grant Agreement Number 327142

"**PFRPStruJoin**"

Structural Joints for Building Frames of Pultruded Fibre Reinforced Polymers

PIEF-GA-2012-327142

Overview of the project implementation

This project was divided into the following four Work Packages (WP):
1. WP1: Management, coordination and dissemination.
2. WP2: Preparation of research activities.
3. WP3: Execution of research and innovation activities.
4. WP4: Evaluation, demonstration and validation.

The tasks in each of the WPs were outlined in the work plan that is reproduced below in grey shaded blocks (two-year project). The actual work plan of the project tasks is indicated in black shaded blocks.

Work Package and Tasks	**Timeline (years)**							
	1				**2**			
From August 2013 Quarter	1	2	3	4	5	6	7	8
WP1 – Management, coordination and dissemination								
WP2 – Preparation of research activities								
Task 2-1 – Literature review and characterization of the state-of-the-art								
Task 2-2 – FE modelling of composites								
WP3 – Execution of research and innovation activities								
Task 3-1 – Advanced Finite Element (FE) analyses								
Task 3-2 – Procedure for frame joint design								
Task 3-3 – Influence of joints on pultruded FRP-frame behaviour								
Task 3-4 – Drafting of a short design guide								
WP4 – Evaluation, demonstration and validation								

According to the work plan, all tasks have been implemented and mostly completed during the duration of the project:

WP1 – task 1-1

Management, coordination and dissemination

This task covers the management and coordination of this project and the dissemination of the research results. Task 1-1 is a transverse activity of the project and was designed to support and assess the remaining WPs. The management activities have been conducted as described in section B4.3 of the proposal. Major findings from the project have been presented and discussed in technical meetings of the Technical Committee 10 (Connections) of the European Convention for Constructional Steel (ECCS/TC10) in Karlsruhe, October 10-11, 2013, Stockholm, October 2-3, 2014, and Papendrecht, April 16-17, 2015, the British Construction Steel Association (BCSA) Connections Group, November 27, 2013, May 14, 2014, November 19, 2014, and May 13, 2015, seminars at Bristol University and Imperial College London (S1 and S2 below), and International Conferences (P5 and P6 below).

WP2 – task 2-1

Preparation of research activities: literature review and characterization of the state-of-the-art

The state-of-the-art review discussed effective joining techniques between fibre reinforced polymer (FRP) pultruded members and addressed their special challenges. Existing experimental and analytical work was compiled and the principal available results were collected. The review further looked at current design rules and reflected the current knowledge on the topic, especially from a technical point of view.

Predicted time of completion: 3 months (the task was completed on time)

The objectives for this task were fully met: the researcher (i) developed a better understanding of the behaviour of connections and frame joints for pultruded FRP building structures, and (ii) identified the gaps in knowledge and produced a comprehensive review of the behaviour of bolted connections and joints between FRP pultruded members.

Milestones: Publication P1 below.

WP2 – task 2-2

Preparation of research activities: FE modelling of composites

This task was originally planned to further quantify the state-of-the-art. Advanced FE analyses were planned to be carried out and correlated/benchmarked to existing experimental results from tests on joints and connections conducted by the Warwick group. This task has been found to be very complex to implement without preliminary research work into the specificities of composite modelling. Because the School of Engineering Group has no expertise in this specific area, the researcher spent a number of months trying to solve this problem and seeking for external advice on how to tackle the model. Although this caused a significant delay in completing the task, the intensive research on the computational modelling of progressive failure of composites, by means of implicit and explicit solvers, clearly brought benefits to the research work. The researcher implemented and validated an FE model of an open hole in tension (OHT) specimen. The OHT for composite materials is a challenging problem because failure involves complex mechanisms such as fibre breakage, matrix cracking and delamination. In addition, the OHT strength and dominant failure modes can depend on geometrical parameters and material properties, such as hole diameter, stacking sequence and ply thickness.

Predicted time of completion: 6 months, and in parallel with task 2-1 (this task started in November 2013, with a three month delay. There was also a six month delay in completing this task.)

The objectives for this task were met: the researcher validated a three-dimensional FE model that is able to represent all the main features, up to ultimate failure, of the structural behaviour of composites.

Milestones: Publications P2 and P3.

WP3 – task 3-1

Execution of research and innovation activities: advanced FE analyses

This task was partially merged with the above task 2-2 as the research work involved was clearly complementary.

Nonlinear FE techniques consistent with experimentally verified techniques from Task 2-2 and experimental results from the University of Pittsburgh, USA, (research collaboration) were implemented in this WP. The numerical results were used to supplement test data and give a more accurate description of the loading paths in the joints and connections components.

Predicted time of completion: 12 months (this task effectively started in May 2014, with a three month delay. There was also a six month delay in completing this task.)

The objectives for this task were fully met: a complete FE procedure was developed to assist in the analysis and design of practical bolted connections, and implementation, execution and application of comprehensive set of parametric studies that will provide information for derivation of appropriate design rules for bolted connections between FRP connecting components and FRP pultruded members.

Milestones: Publications P3 and P4.

WP3 – tasks 3-2, 3-3 and 3-4

Execution of research and innovation activities: procedure for frame joint design, influence of joints on pultruded FRP-frame behaviour, drafting of a short design guide

These three tasks were not completed during the project duration. For scientific reasons, the researcher and the scientist in charge have decided to pursue a progressive failure modelling based on Continuum Damage Mechanics and Cohesive Zone Approach to verify and benchmark the FE composite models. The effort has been considerable and this has caused a significant delay in keeping to the original timetable. This had impact on the start date of tasks 3-2, 3-3 and 3-4. The researcher felt that the pursued scientific approach was beneficial to the work and to the added value of being in contact with various aspects of advanced composite modelling and this was clearly an asset. However, both researcher and the scientist in charge are committed to carry out (and report to the Commission) this task after the two year period of the project.

Milestones: Publications P7, P8, and others.

WP4 – task 4-1

Evaluation, demonstration and validation

The outcomes of this study had a major impact on structural engineering research and assisted the preparation of recognized design rules for structural joints in pultruded FRP building frames.

The researcher was very successful in this task and was able to present the main results in

prestigious Universities (seminars S1 and S2) and International Conferences (P5 and P6).

Predicted time of completion: 6 months (the task was completed on time).

The main objective (to evaluate the project and disseminate results) was met.

Milestones: Final project report.

Overview of the research training results

The research training objectives outlined in the PRDP were fully met.

The researcher has joined several training courses at the University's Learning and Development Centre to in order to bolster her leadership and management skills and strengthen a leading independent position. These courses are listed below:

1. Introduction to networking (half-day course, November 2013).
2. Career development: interview success (two-hour course, November 2013).
3. Career development: evidencing your skills (two-hour course, January 2014).
4. Establishing yourself: productivity and people (full-day course, February 2014).
5. Assertiveness workshop (full-day course, March 2014).

Between November 2013 and January 2015, the researcher acted as the representative of the School of Engineering at the University Research Staff Forum (RSF). The RSF serves as a general networking function and provides a focus for (i) gathering research staff views on issues such as induction, training, development opportunities, etc., (ii) discussing key issues with University staff (the Vice Chancellor, Director of Personnel, Director of Careers, Director of Research Support Services), (iii) influencing Warwick policy and practice and help to improve the experience of being a researcher at Warwick, and (iv) developing representatives skills through chairing, shaping and recording discussion at the meetings and representing the views of fellow research staff. The attended several meetings and made significant contributions towards (i) the improvement of the Library resources, and (ii) the development of Warwick's action plan on HR excellence in research and HR excellence.

The researcher also attended the following seminars:

1. *Three-dimensional brittle fracture: configurational-force-driven crack propagation*, Dr. Mohaddeseh Mousavi Nezhad, University of Warwick.
2. *Resilient minimal-damage post-tensioned steel frames*, Dr. Angelos Tzimas, University of Warwick.
3. *Damage-based design of steel structures*, Dr. George Kamaris, University of Warwick.
4. *Micro-mechanics and multi-scale, hierarchical modelling: recent developments*, Dr. Eddie McCarthy, University of Manchester.
5. *Multi-scale modelling of composites: towards virtual testing and design*, Dr. Cláudio Lopes from IMDEA Materials, University of Manchester.
6. *Sustainable Hazard Resistant Construction Using Indigenous Materials - Bamboo Construction in Darjeeling and Sikkim*, Dr. Kent Harries from the University of Pittsburgh, University of Warwick.
7. *Joining technologies for fibre-reinforced polymer composite materials* (full-day event, involving industry and academia, May 2014), University of Warwick.

The researcher was also involved in several outreach activities, the most important of which was done in collaboration with Mrs. Karen Bradbury, Principal Teaching fellow and Director of Undergraduate Admissions of the School of Engineering, for secondary schools, with a target audience of children aged 13-14.The principal objective was the promotion of careers in science and engineering among teenage students.

The researcher also had the opportunity to participate in the EuroScience Open Forum, ESOF2014, and the Marie Curie satellite event on *Transferable Skills: added values for your CV* held in Copenhagen, June 2014. This was a unique and valuable experience as the researcher was able to learn about new discoveries in a large number of fields, meet Nobel laureates, researchers from all disciplines, discuss career perspectives and links of science to business, and participate in lively science policy debates with major European and Danish politicians.

Exploitation and dissemination of results

List of scientific publications

International journals

P1 Girão Coelho AM, Mottram JT (2015). A review of the behaviour and analysis of bolted connections in pultruded fibre reinforced polymers. Materials and Design 74, 86-107. http://dx.doi.org/10.1016/j.matdes.2015.02.011

P2 Girão Coelho AM (2015). Finite element guidelines for simulation of delamination dominated failures in composite materials validated by case studies. Archives of Computational Methods in Engineering (in press). http://dx.doi.org/10.1007/s11831-015-9144-1

P3 Girão Coelho AM, Mottram JT, Harries KA (2015). Finite element guidelines for simulation of fibre-tension dominated failures in composite materials validated by case studies. Composite Structures 126, 299-313. http://dx.doi.org/10.1016/j.compstruct.2015.02.071

P4 Girão Coelho AM, Mottram JT, Harries KA (2015). Bolted connections of pultruded GFRP: implications of geometric characteristics on net section failure. Composite Structures 131, 878-884. http://dx.doi.org/10.1016/j.compstruct.2015.06.048

International conferences

P5 Girão Coelho AM, Mottram JT, Harries KA (2015). Parametric study of net section failure of pultruded connections with three-dimensional finite element approach. Presented at ICCS18 - 18th International Conference on Composite Structures, Lisbon, Portugal, 15-18 June 2015.

P6 Girão Coelho AM, Matharu N, Mottram JT. Parametric study of net section failure of pultruded connections with three-dimensional finite element approach. To be presented at 5th ECCOMAS Thematic Conference on Mechanical Response of Composites, Bristol, UK, 07-09 September 2015.

In preparation

P7 Girão Coelho AM, Matharu N, Mottram JT. Virtual characterization of delamination failures in pultruded GFRP composite angle cleats. To be submitted to Journal of Composites for Construction, October 2015

P8 Girão Coelho AM, Lopes CSF, Može P, Mottram JT. Numerical study of the influence of end distance on shear-out strength of bolted connections of pultruded GFRP. To be submitted to Composites Part B: Engineering, December 2015

Seminars

S1 Girão Coelho AM (2015). Structural joints for building frames of pultruded fibre reinforced polymers: overview and principal results of PFRPStruJoin. Presented at University of Bristol, UK, 28 April 2015 by kind invitation of Professor Stephen R. Hallett.

S2 Girão Coelho AM (2015). Structural joints for building frames of pultruded fibre reinforced polymers: overview and principal results of PFRPStruJoin. Presented at Imperial College London, UK, 20 May 2015 by kind invitation of Professor Silvestre Pinho.

Conclusions of the project

Research undertaken as part of the PFRPStruJoin project has produced the following important results:

1. A comprehensive literature review of the state-of-the-art experimental and analytical methodologies adopted in the construction industry for the design of mechanically fastened connections and joints in pultruded fibre reinforced polymer framed structures:

- Results and conclusions obtained from the published literature relating to the effects of critical parameters, which included geometry, material properties, configuration, connecting components, fasteners, lateral restraint, etc. on the mechanical behaviour and failure modes were discussed in the light of addressing gaps in knowledge that need resolving to prepare design guidance that is reliable and robust.
- Further research required to improve the design of composite mechanically fastened joints was identified as a result of this review.

2. Guidelines for a reliable failure analysis of composites in the context of the FE method:
   - Modelling of intralaminar failure modes using continuum damage mechanics.
   - Modelling of interlaminar delamination using a cohesive zone approach.
   - Implementation of regularization techniques.
3. Validation of FE model for failure analysis of composites:
   - Double-cantilever and end-notched flexural specimens.
   - OHT specimen, which is a very challenging scientific problem because failure involves complex mechanisms such as fibre breakage, matrix cracking and delamination. In addition, the OHT strength and dominant failure modes can depend on geometrical parameters and material properties, such as hole diameter, stacking sequence and ply thickness.
4. Virtual testing of bolted connections of pultruded GFRP:
   - Development and validation of a nonlinear FE modelling methodology to predict the initiation and damage progression in notched FRP laminated plates subjected to increasing in-plane tension load.
   - Implications of geometric characteristics on net section and shear-out failures; based on the numerical results, design recommendations for minimum edge and end distances, and pitch and gauge spacing for bolts are given (support to revisiting current geometry requirements of the ASCE pre-standard).
   - Tying resistance and structural robustness of bolted joints.