PREDICTING FAILURE MECHANISM OF SYNTACTIC FOAM CORE SANDWICHES WITH MULTI-LAYERED CORE

By

Suryanath Ghimire

Submitted in Partial Fulfilment of the Requirements for the Award of the Degree of

Doctor of Philosophy in School of Civil Engineering and Surveying,

University of Portsmouth

October 2020

Acknowledgements

I would like to express my sincere acknowledgement to all who involved directly or

indirectly in this research project.

Firstly, I would like to thank Dr Jiye Chen, Reader in Structural Composites at the University of Portsmouth, School of Civil Engineering and Surveying, for all his invaluable supervision, support and mentorship from the inception of my PhD journey. As a supervisor, he did not only play a supervision role but also mentored and supported me to complete this research project appropriately. Obviously, PhD journey is not straightforward, but his invaluable knowledge and guidelines during difficult situations helped me a lot to bring my research project on track.

Secondly, I would also like to thank Dr David Begg, Senior Lecturer at University of Portsmouth, School of Civil Engineering and Surveying, for all his invaluable feedback and comments on my thesis during PhD assessment as an internal assessor. I would like to acknowledge his in-depth feedback and comments.

I would like to thank Teresa from the IT department for continuous support to install different software and help during various IT problems which was remarkable.

Finally, this research project would not be possible to complete without constant encouragement and support from my wife, Sarita Neupane Ghimire. I should also praise the blessings of my parents, who always look forward to my good fortune in life.

Abstract

This thesis presents the results of optimizing loading capacity of the sandwich panel by proposing a functionally graded sandwich panels and predicting the detailed failure mechanism of such panels. This study implemented the finite element based Extended

Cohesive Damage Model (ECDM) to study the detailed failure mechanism of functionally graded sandwich panel.

This research first time explored an in-depth investigation on the failure mechanism of syntactic foam sandwiches with a multi-layered core. This sandwich consists of laminated fibre sheets on the top and bottom individually, and a syntactic foam core with multiple graded layers between two laminated sheets. The failure mechanism of this kind of syntactic foam sandwich panels were studied through numerical modelling under quasi static three-point bending. The prediction showed perfect agreements with experimental work on investigating the sandwiches with homogeneous core and the core with four functionally graded layers. This investigation did not only found that the failure mode of a sandwich panel with the multi-layered core is shear failure dominated delamination but also found an excellent mechanical performance when the core has multiple graded layers in the investigated sandwiches compared to the case of the homogenous core. The delamination was along with the path close to the interface between the core and the bottom sheet. The correlation between loading capacity and the number of graded layers in the core of the investigated syntactic foam sandwiches is introduced for the first time. The ECDM predicted loading capacity of the investigated sandwich panel with an 8-layered core is increased ultimately by 61% compared to the case with the homogenous core.

The geometric ratio, depth to span, of sandwich panel affects failure behaviour. Hence, it is the first time that this investigation explored geometrical ratio effects on the failure mechanism of functionally graded sandwiches with multi-layered cores. The FGSP showed different failure modes when their geometrical ratio between the depth and the span varies. Furthermore, this research also introduced the correlation between the failure load and the geometrical ratio of the FGSP with a multi layered in the core.

The outcomes of this research contribute to academic knowledge, and industrial applications are summarized as follows:

- It is the first time that this work explored the detailed failure mechanism of functionally graded syntactic foam core sandwich panel having more than four layers in the core using ECDM;
- It introduced the correlation between failure load and the number of layers;
- Likewise, geometric ratio effects on the failure mechanism of functionally graded sandwich panels are studied;
- Finally, it also introduced the correlation between failure load and the geometric ratio;
- Academically, these novel contributions can be used for future research as a benchmark. Likewise, this correlation can be used to predict the failure mechanism of the intermediate number of layered cores to gain a general overview of the initial design of FGSP;
- These findings can be used to carry out further researches and to manufacture sandwich panels for various engineering applications with different geometrical depth-span ratios and variable layered sandwich cores;
- This investigation also showed that the ECDM is a robust tool for predicting failure mechanism of syntactic foam sandwiches.

Abbreviations

$\mathbf{a}_i$ Additional DoFs

CZM Cohesive Zone Model

D An expression for damage scale factor

E Young’s modulus

ECDM Extended Cohesive Damage Model

��������Cohesive force vector

$\mathbf{f}_{ext}$The equivalent nodal force vector for enriched freedoms $_{a}$

$\mathbf{f}_{ext}$The equivalent nodal force vector for standard FEM

^{u} freedoms

G Shear modulus

G_c Total fracture energy

G_{Ic} and G_{IIc} Mode-I and mode-II critical Fracture energy

H_{Γ_d} Heaviside function

i Standard degree freedoms

j Enriched degree freedoms

$\mathbf{K}^{aa}$ The stiffness matrix associated with the enriched FE approximation

$\mathbf{K}^{uu}$ The stiffness matrix associated with the standard FE approximation

$\mathbf{K}^{ua}$/ $\mathbf{K}^{au}$ Coupling between enriched approximation and the standard FE approximation

L_1 and L_2 The effects of enrichment and cohesive force l_{crack} The

characteristic length of a crack

N Interpolation function

N_i Standard FEM shape functions

N_j Enriched FEM shape functions

t_0 Initial cohesive traction

�� The external traction

��0��and ��0��Initial normal and shearing traction components ��Cohesive

tractions in local normal (n) and tangential (s) ��/ ������h

������h directions

$\mathbf{u}_i$ Displacement

��h(��) The displacement field

XFEM eXtended Finite Element Method Γ^h A

boundary

Γ_d The discontinuity

����������Crack surface due to cohesive force $\Gamma_{����h}$

����Displacement jump

$\Phi(\mathbf{x})$ enriched function for discontinuity

τ_0 Initial traction

ε_0 Initial strain

Ω Domain

$\boldsymbol{\Omega^-/\Omega^+}$ Two different sides of the domain

$\Re$ An operator that represents ultimate equilibrium ν Poisson ratio

Declaration

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

Signed Date 26th September 2020 STATEMENT 1

This thesis is being submitted in partial fulfilment of the requirements for the degree of PhD.

Signed Date 26th September 2020

STATEMENT 2

This thesis is the result of my own independent work/ investigation, except where otherwise stated. Other resources are acknowledged by explicit references. Signed

Date 26th September 2020 STATEMENT 3

I hereby give consent for my thesis, if accepted, to be available for photocopying and inter-library loan, and for the title and summary to be made available to outside organizations.

Signed Date 26th September 2020

Dissemination

Papers published in the International Journal with high impact factors:

1. Ghimire, S. and Chen, J., 2019. An extended cohesive damage model study of geometrical ratio effects on failure mechanisms of functionally graded sandwiches with multi-layered cores. ***Composite Structures***, *224*, p.110999.
2. Ghimire, S. and Chen, J., 2020. Predicting fracture mechanisms in synthetic foam sandwiches with multi-layered cores using extended cohesive damage model. ***Engineering Fracture Mechanics***, *223*, p.106719.

Conference papers and activities:

1. S. Ghimire, J. Chen. A Novel Sandwich composite with Graded Layered Core Predicted by Extended Cohesive Damage Model- **12th International Conference on Sandwich Structures (ICSS-12)** Lausanne- Switzerland, 19-22 August 2018- (***Published conference paper)***
2. **Faculty Research conference**: University of Portsmouth, The United Kingdom (7th June 2018) Predicting failure mechanism of synthetic foam core sandwiches with multi-layered cores (***Poster presentation***)
3. **Faculty Research conference**: University of Portsmouth, The United Kingdom (18th

June 2019) Predicting failure mechanism of synthetic foam core sandwiches with multi-layered cores ***(Short Talk Presentation)***

4. S. Ghimire and J. Chen, 2019; A Modelling Study on Failure Mechanism of Synthetic Foam Sandwiches with Multi-Layered Cores Using Extended Cohesive Damage Model (***Published paper*** in ACIC. ***Short talk presentation*** as well as a ***poster presentation*** in the Conference) - Proceedings of the 9th **Biennial Conference on Advanced Composites in Construction - 2019** held at the University of Birmingham, U.K. on 3rd - 5th September 2019.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.0 Overview

This chapter introduces the overall themes of this thesis. It also places the motivation for the research work into context. It discusses the rationale behind carrying out this research which is followed by a summary of the research project, and aims and objectives. This chapter also presents the contributions of this research. Finally, it presents a thesis outline.

1.1 Motivation and background

There are various catastrophic events, such as earthquakes, that happened in Nepal in April 2015, which caused the death of more than 9000 people and injured another 22,000 people. Earthquakes do not kill people directly, but structural damage as a result of earthquakes kill people. Different factors are associated with identifying the effects of earthquakes. One of them is structural damage due to structural failure. It is crucial to study the failure mechanism of structures that play a pivotal role in the destruction of the structure. It is possible to significantly decrease casualties if we can predict the fracture behaviour of different structures and design them accordingly in the design phase. Numerical predictions during the design stage can help to identify possible damage. Likewise, structural retrofitting is one of the crucial ways to decrease structural failure in the post-earthquake stage. Numerical predictions that will help for retrofitting can also be applied to examine the detailed failure mechanism of partly damaged structures.

Significant research carried out to optimize design solutions that will guarantee the safety of structures but without compromising the economic viability of the structure. Lightweight structures are one of the best solutions to decrease damage during an earthquake. Lightweight structures will help to reduce the total mass, which is associated with structural failure due to shock and other loading conditions.

Composite sandwich panels are innovative options to build lightweight structures. There are wide applications of composite sandwich panels in various industries such as; automobile, aeronautical, civil, and others (Chandra et al., 2017). Composite sandwich panels are manufactured by attaching two thin outer layers of fibre laminates with core in the middle. Fibre laminates having very high material strength. They are separated by a thick layer of the core that is generally a material with lightweight and very low in material properties such as young's modulus and material strengths compared to the top and bottom faces (Antony Arul Prakash et al., 2012; Chandra et al., 2017; Hassanpour Roudbeneh et al., 2018). Fibre composite sandwiches show superior advantages Palanikumar et al., (2006) such as increased stiffness compared to other engineering materials (Antony Arul Prakash et al., 2012). There are other different benefits of using composite sandwich panels such as lightweight, resistance to corrosive actions, high strength, high bending stiffness, etc. (Palanikumar et al., 2006; Antony Arul Prakash et al., 2012; Xu et al., 2015).

Usually, composite sandwich panels have honeycomb, corrugated, homogeneous foam and truss cores. However, various applications widely use cores with honeycomb and synthetic foam. For example; various structures and parts in automotive industries, sporting industries and aerospace industries are built using a honeycomb core (Rao et al., 2011; Stocchi et al., 2014; Vitale et al., 2016). Likewise, synthetic foam based cores are used in panels for cladding Shawkat et al., (2008), bridge decks Zoghi, (2013); Tan and Khan, (2018), various parts of ships Mao et al., (2018), turbine blades Tan and Khan, (2018) and flooring in building constructions (Correia et al., 2012). However, this conventional sandwich panel suffers de-bonding or delamination at the interface between fibre-laminate on the bottom and core due to a high value of concentrated stresses and significantly different material properties between the core and laminate at that region Etemadi et al., (2009), which restrains its loading capacity.

Some research has been carried out to mitigate those problems to reduce the material properties gap between face sheets and a core using functionally graded materials (Udupa et al., 2014; Akavci, 2016; Chandra et al., 2017). In their investigations, different materials were mixed at various ratios to design a core with mixed materials as well as the core intended to be single-layered. Composite sandwich panels by varying material properties on core also investigated to reduce the gap between material properties by various researchers (Apetre et al., 2006; Capela et al., 2013). Non-uniform material properties resulted in overall core properties variation. The research found that there were significantly decreased strains in normal and shear directions with the functionally graded core. Discontinuities are eliminated at the interface between the face sheets and the core, resulting in reduced deflection as well as stresses (Apetre et al., 2006; Kashtalyan and Menshykova, 2009).

Analytical, experimental and numerical modelling approaches are usually used to study the failure behaviour of the composite sandwich panel in the past. In the analytical method, the mechanical behaviour of composite sandwich panels having functionally graded cores (FGC) are calculated using various formulations based on the high order plate theory. These analytical approaches employ a varieties of theories, for example: third-order zig-zag model (Icardi and Ferrero, 2009), 3-D elasticity equation (Apetre et al., 2006), classical deflection formulae (Lashkari and Rahmani, 2016) and polynomial equations (Kashtalyan and Menshykova, 2009). However, it is difficult to predict the failure mechanism of multi-layered composite sandwich panels in the structural level through these analytical approaches. Likewise, different experiment tests are carried out to investigate the failure mechanism of sandwich panel with FGC (Avila, 2007; Capela et al., 2013). Capela et al. (2013) conducted experimental tests in examining the impact of variable densities of foam core to the bending response of sandwich panels. There was a significant improvement on the performance of a 4-layered sandwich panel having FGC on bending stiffness and resistance compared to traditional sandwich panels having homogeneous cores. However, the experimental approach is costly in investigating the failure mechanism of the composite sandwich panel and optimising its behaviour. On the other hand, the numerical modelling approach compared to other different methods is less time consuming and so can be cost-effective.

Likewise, the geometrical ratio of composite sandwich panels also affects their failure behaviour. Different research methods have focused on the study of the effect of the geometric ratio on the mechanical behaviour of sandwich panels. Basaruddin et al. (2015) experimentally studied the impact of the depth/span ratio on the failure behaviour of aircraft sandwich panels under bending loads. They considered various spans such as 125 mm, 80 mm, 70 mm and 55 mm of honeycomb core sandwich panels. The deflection highly influenced by span length. Bending stiffness of the panels decreased with increased in span length. Experimental results showed good agreements with analytical calculations calculated by Basaruddin et al. (2015) based on the analytical formulation formulated by Kelsey et al. (1958). The critical load decreased, but deflection increased from short span to long-span lengths in honeycomb core sandwich panels.

The effect of thickness is also investigated by Wang et al. (2015), who concluded that increasing the depth-to-span ratio will lead to increasing bending strength and bending stiffness. As a result of the increase in the depth to span ratio, Wang et al. (2015) argued that shear capacity of the sandwich panels is increased and resulted improved bending strength as well as bending stiffness. Yan et al. (2018) studied the failure mechanism of composite sandwich panels with metal foam having varied densities and found that the shear failure of foam cores was a major failure mechanism. However, their investigation merely focused on a sample with one density and the varied number of plies in faces. Likewise, Fang et al. (2016) studied the impact of the increasing thickness of faces resulted in improved stiffness, flexural rigidity and ultimate load. See the literature review chapter two for more details.

1.2 Research Gap

When referring to the literature review chapter two, it found that there are varied researches based on analytical, numerical and experimental approaches which focused on studying the failure mechanism of functionally graded sandwich panels (FGSP). However, there are limited research explored the detailed failure mechanism of multi

layered synthetic foam core sandwich panels. Analytical approaches have difficulty in predicting the failure mechanism of multi-layered composite sandwich panels in the structural level. Likewise, experimental methods are costly in investigating the failure mechanism of the composite sandwich panel and optimising its behaviour. There is still a lack of research investigating the detailed failure mechanism of functionally graded sandwich panels having more than four layers in the core.

Furthermore, as mentioned in the earlier section, there are significant effects of geometric ratio in the behaviour of sandwich panels. However, the depth-span ratio effects of functionally graded sandwiches with multi-layered cores in which material properties are varied layer by layer in the core were investigated very little in the past. Hence, apparent research gaps are studying the detailed failure mechanism of functionally graded sandwich panels with syntactic foam cores as well as exploring the geometric ratio effects of functionally graded sandwich panels. The summary of research gaps are as follows:

- Various studies have been carried out by researchers to improve the mechanical behaviour of sandwich panels. Still, they are limited to homogeneous cores or up to four layers in the core;
- Analytical solutions of FGSP are limited to linear elastic stiffness;
- Different experimental tests have been carried out, but they are limited to single layer homogeneous core or up to four layers in the core;
- Previously used numerical modelling and analytical approaches cannot accurately predict the detailed failure mechanism of FGSP;
- Hence, there is a clear research gap studying the detailed failure mechanism of sandwich panels having multi-layers, more than four layers, in the core;
- This research project will fulfil these research gaps by studying the detailed failure mechanism of sandwich panels with multi-layers in the core.

1.3 Research Aims and Objectives

1.3.1 Research Aims

The main aim of this research project is to predict the detailed failure mechanism of syntactic foam core sandwiches with multi-layered cores using the Extended Cohesive

Damage Model (ECDM).

1.3.2 Research Objectives

The main objectives of this research project are as follows:

➢ To predict the failure mechanism of sandwich panels using ECDM; ➢ To validate ECDM predictions on the failure mechanism of sandwich panels with experimental test results;

➢ To explore the detailed failure mechanism of functionally graded sandwich panels with more than four layers in the core;

➢ To introduce the correlation between failure load and the number of layers of functionally graded sandwich panels with more than four layers in the core; ➢ To study the geometric ratio effects on the failure mechanism of functionally graded sandwich panel with more than four layers in the core;

➢ To introduce the correlation between the geometric ratio and the failure load of functionally graded sandwich panels with more than four layers in the core.

1.4 Research Contributions

This research will contribute to the academia and within the industry by carrying out a study that will predict the detailed failure mechanism as well as the depth-span ratio effects on the failure mechanisms of functionally graded sandwich panels. Academically, these novel contributions can be used for future research as a reference. Likewise, this correlation can be used to predict the failure mechanism of the other intermediate number of layered cores, and it can be used to gain a general overview of the initial design of FGSP. This investigation provides a sustainable approach to predict the detailed failure mechanism of the FGSP with a multi-layered core in further research and industrial applications.

It is the first time that this research studied the detailed failure mechanisms and introduced some correlations. Firstly, this research carried out the numerical analysis to study the detailed failure mechanism of functionally graded sandwich panels with more than four layers in the core. Secondly, it introduced the correlation between the number of layers and the failure load of FGSP with more than four layers in the core. Thirdly, it studied the geometric ratio effects on the failure mechanism of FGSP with more than four layers in the core. Finally, it also introduced the correlation between the failure load and geometric ratios of FGSP with more than four layers in the core.

1.5 Thesis Outline

The organization of other parts of this thesis are as follows:

Chapter 2 presents the reviewed articles on the state-of-the-art in design and analysis of composite sandwich panels. This chapter discusses the historical background and application of composite sandwich panels in various engineering structures. It also presents the current works of literature on core and face sheet materials behaviour, which is followed by research on functionally grading of materials to improve the mechanical behaviour of sandwich panels. Various kinds of studies to predict the failure mechanisms of functionally graded sandwich panels are also reviewed. Besides, analytical approaches and numerical solutions to predict the detailed failure mechanism of functionally graded sandwich panels are also critically reviewed. Likewise, it also considered existing pieces of literature on experimental tests.

Chapter 3 describes the methodological aspect of this research project. The extended finite element method (XFEM) and cohesive zone model (CZM) are widely used tools to predict the failure mechanism of sandwich panels. However, there are limitations in using these tools to predict the detailed failure mechanism of functionally graded sandwich panels. Hence, this research used extended cohesive damage model (ECDM) to study the failure mechanism of FGSP. This chapter discussed the advantages of using ECDM as well as theoretical formulations of ECDM and methodology choices followed by the advantages and disadvantages of other methods. This chapter also described the concerns related to FEA modelling of multi-layered sandwich panels. Finally, there is a detailed discussion of the modelling technique using ECDM in ABAQUS.

Chapter 4 presents a comprehensive study on failure mechanisms of functionally graded sandwich panels. Initially, validation work is carried out for a single-element test under tensile, shear and mixed-mode loading cases using ECDM element. There is an excellent agreement on ECDM predictions, analytical solutions and cohesive zone modelling. Furthermore, a detailed failure mechanism of a sandwich panel with a homogeneous core and four-layered core were predicted using ECDM. ECDM predictions are validated with experimental test results and analytical solutions with excellent agreements. Afterwards, a detailed failure mechanism of functionally graded sandwich panels with more than four layers in the core is carried out. Finally, the correlation between failure load and the number of layers of functionally graded sandwich panels with more than four layers in the core is introduced.

In chapter 5, geometric ratio effects on the failure mechanism of functionally graded sandwich panels with more than four layers in the core are studied and presented. The geometric ratio effects of varying span lengths from 15 mm to 100 mm are studied. The correlation between the geometric ratio and failure load of functionally graded sandwich panels with more than four layers in the core is introduced.

Chapter 6 closes the thesis, reviewing the work carried out and draws conclusions about key parts of the work that are undertaken. Finally, future works are discussed with a particular focus on the application of ECDM and further study on functionally graded sandwich panels.

Chapter 2

Literature Review

2.0 Overview

This chapter presents a review of the literature on the state-of-the-art composite sandwich panels. Historical background of sandwich panels and its various industrial applications are reviewed. It also reviewed the literatures on the failure mechanism of sandwich panels, functionally graded materials concepts, functionally graded sandwich panels, and failure mechanisms of sandwich panels.

This chapter reviewed numerous experimental tests to investigate the failure mechanism of composite sandwich panels. Likewise, different analytical solutions and numerical methods to predict failure mechanism of composite sandwich panels are also critically reviewed.

2.1 Historical background of sandwich panels

The concept of the sandwich panel was thought to evolve from the 19th century if we look at the history of the sandwich panel (Allen, 2013). According to Paul et al. (2002), de Havilland started to produce nonstrategic-material spruce and balsa to construct a sandwich structure during World War II (Bitzer, 1997). It is believed that this concept has had a considerable impact on the evolution of new materials in various industries, such as the automotive and construction industries. However, it was not used on different engineering applications until the Second World War (Paul et al., 2002). The concept and use of sandwich panels were widely considered since then.

2.1.1 Application of sandwich panels in civil engineering

In civil engineering structures, the uses of composite sandwich panels are relatively overlooked (Karlsson and TomasÅström, 1997) which is due to the cheap availability of other traditional construction materials such as concrete and steel (Islam and Aravinthan, 2010). However, due to certain advantages to other construction materials, sandwich panels are becoming apparent and being used more often (Keller, 2007). It is argued that the sandwich panel has become a viable solution in the civil construction industry (Reis and Rizkalla, 2008; Van Erp and Rogers, 2008). Flooring is one of the best application of sandwich panels in the construction industry due to its lightweight and strength compared to traditional materials such as flooring with wood or concrete (Karbhari, 1997). In addition, it can also be used in other civil engineering applications such as different structural members, bridge deck construction, wall partitions, cladding and many others (Shawkat et al., 2008; Zoghi, 2013; Tan and Khan, 2018).

2.1.2 Sandwich panels vs I-Beam sections

As shown in Figure 2-1, sandwich panels are characterised as two thin layers on top and bottom face sheets, which are separated by comparatively thick core material (Bozhevolnaya and Lyckegaard, 2005; Islam and Aravinthan, 2010). Generally, the core material is lightweight and has low density and stiffness.

Composite sandwich panels are manufactured by attaching two thin layers of fibre laminates having very high material strength. These layers of fibre laminates are separated by a thick layer of the core that is generally a lightweight material with very low material properties as compared to the top and bottom faces (Antony Arul Prakash et al., 2012; Chandra et al., 2017; Hassanpour Roudbeneh et al., 2018).

Core

Figure 2-1: 3D view of the sandwich panel

Fibre composite sandwiches show superior advantages such as increased stiffness compared to other engineering materials (Palanikumar et al., 2006; Antony Arul Prakash et al., 2012). There are other different benefits of using composite sandwich panels such as their lightweight, resistance to corrosive behaviour, high strength and high bending stiffness. (Palanikumar et al., 2006; Antony Arul Prakash et al., 2012; Xu et al., 2015). These properties of the sandwich panels are highly exploited, and the application of composite sandwich panels has become radically widespread.

Sandwich panels show excellent bending as well as shear stress resistance capability, which is similar in behaviour to I-Beam sections (Bozhevolnaya and Lyckegaard, 2005). Figure 2-2 represents the comparison between an I-beam section and a sandwich panel.

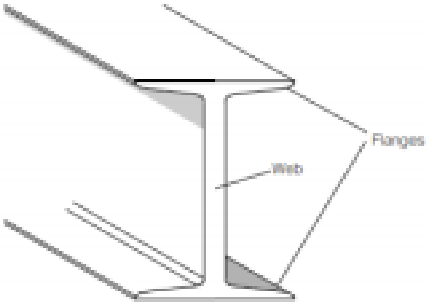

Figure 2-2: Comparison of I-Beam (Hexcel, 2000) on the left and 3D sandwich panel on the right

Face sheets are comparable to flanges in I-Beam sections; with the top face sheet acting as a compression member and the bottom face sheet as a tension member. As a result, face sheets play a significant role in bending resistance due to their high stiffness values. Whilst, the core, similar to the web in I-Beam, demonstrates excellent shear stress resistance by providing a high moment of inertia as well as rigidity.

However, core materials in sandwich panels can be used with very low material properties compared to face sheets. The wider area of core gives the greater capacity to transmit the transverse load and reduces local stresses (Hexcel, 2000). Hence, the core of sandwich panels is widely manufactured with very light and very low stiffness values materials. It can be seen from Table 2-1 that stiffness and flexural strength are improved when the core is inserted in between solid material. Stiffness is drastically enhanced more than five times when the thickness is increased three times. Likewise, flexural strength is also increased around three times. Despite the increased stiffness and flexural strength, the weight of the panel remains comparable. On the other hand, there is a small change in the weight of the panels.

Table 2-1: The relative stiffness and weight of sandwich panels (Hexcel, 2000)

	Solid material	**Core thickness (t)**	**Core thickness (3t)**
Stiffness	1.0	7.0	37.0
Flexural strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

It is argued that composite sandwich panels compared to reinforced concrete (RC) panels have better potential in cladding system applications (Shawkat et al., 2008). Comparison between reinforced concrete panels and composite sandwich panels based on weight is presented in Table 2-2.

Table 2-2: Comparison between reinforced concrete panels and composite sandwich panels based on self-weight of the same size (Shawkat et al., 2008)

RC panels	46-67 Kg
Composite sandwich panels	7-10 Kg

However, the actual properties and performance of sandwich panels depend upon various factors such as; face sheet, core and bonding material choices; geometry; and boundary conditions. Material choices are dependent on the application of the sandwich panels, which can be tailored by carefully selecting materials and prudent design.

2.1.3 Face sheet materials in sandwich panels

The material in the face sheets plays a significant role in the mechanical behaviour of composite sandwich panels. They are holding entire tensile and compressive stresses. Face sheets are exposed to the environment; hence, other environmental factors also need to be considered carefully in the material selection process.

Wood face sheets

Traditionally in the aerospace industry, wood veneers were widely used as top and bottom laminates when sandwich panels were designed because they were widely available, and were very light in weight (Plantema, 1966). However, plywood was commonly used in the construction industry as their weight does not play a significant role.

Metal face sheets

Although wood materials are used in composite sandwich panels, the use of other metal materials; such as steel, aluminium and titanium has become popular. They are broadly used in the aircraft industry and construction industries as it was to increase the mechanical behaviour such as structure's stiffness and strengths. So, extensive research has been carried out to investigate the mechanical behaviour of composite sandwich panels with metal face sheets and different core materials. Various research using aluminium alloys are widely mentioned in different pieces of literature (Davies, 2008; Crupi et al., 2011; Mohan et al., 2011; Zu et al., 2013; Yan et al., 2018). Aluminium foam is considered as a light-weight material and is preferred as a core material in composite sandwiches. However, aluminium foam on its own has not been used as a structural material due to its weak mechanical properties (Yan et al., 2018).

Steel panels with aluminium foam are also reported by various researchers such as (Zu et al., 2013). The stainless steel used with aluminium foam cores and experimental impact tests were carried out by Mohan and others (Mohan et al., 2011). However, Yan et al. (2018) argued that the benefit of the lightweight sandwich panel had been undermined by using steel which is comparatively heavy as compared to other fibre materials or aluminium foam. Hence, the various researcher recommended the use of other non-metals such as fibre materials as face sheets. Zhu and Chai (2013) and Shi et al. (2014) have validated this in their research. Shi et al. (2014) have carried out investigations using carbon fibre as face sheets with or without kevlar-fibre interfacial toughening.

Glass and carbon fibre as face sheets

It can be seen from the above examples that metal face sheets are one of the options in composite sandwich panel manufacturing. However, the lightweight advantage of using composite sandwiches is undermined with the use of some heavy metallic materials. Hence, the use of carbon or glass fibres can be considered as the best options. Carbon/ Glass fibre have shown excellent mechanical properties such as being lightweight, having high tensile strength and non-corrosive behaviour (Sun et al., 2013). As a result, their use is prevalent in sandwich panel manufacturing (Sun et al., 2013; Zhu and Chai, 2013). However, it is also essential to consider other factors such as location and the environment when choosing face sheet materials such as heat transfer, humidity, moisture, corrosion and compatibility are some of the examples.

2.1.4 Core materials in sandwich panels

Fibre laminates are relatively very expensive as compared to core materials. Core materials are relatively cheap materials as compared to fibre laminates, but they also play a significant role in the performance of composite sandwich panels. Hence, it can be argued that the mechanical behaviour of composite sandwiches can be improved with appropriate core material choice, and it may be one of the economical options. Extensive research has been carried out to improve the mechanical behaviour of composite sandwiches with various core materials.

Hence, it is noted that the scope of this research is limited within core materials to predict the best behaviour of composite sandwich panels with a syntactic foam core. So, the literature on the core materials in sandwich panels are reviewed in more detail in this section.

Metal foam core

Due to its excellent mechanical behaviour, metal foam such as aluminium based foam has brought considerable attention in composite sandwich construction as one of the best options (Yan et al., 2018). Aluminium foam cores are widely considered in various applications and research (Crupi et al., 2011; Mohan et al., 2011; Zu et al., 2013; Yan et al., 2018). Crupi et al., (2011) and Yan et al., (2018) considered aluminium foam sandwich panels, consists of two metal face sheets separated by an aluminium foam core, as an excellent structural member. Various failure modes study of aluminium foam core sandwich with aluminium face sheets was carried out by Mohan and others (Mohan et al., 2011). Sandwich panels with closed-cell aluminium foam core are reinforced, and their mechanical behaviours are studied by Yang et al. (Yang et al., 2015). Similarly, mechanical behaviour under three-point bending of reinforced closed-cell aluminium foam core with carbon fibre as face sheet material was studied (Yan et al., 2018).

Honeycomb core

Honeycomb as the core material in various applications of sandwich panels is another widely used configuration. Hence, it is drawing extensive attention in research. Various researchers such as Zhu and Chai, (2013); Stocchi et al., (2014); Vitale et al., (2016) studied the damage and failure mode of honeycomb core sandwiches. It is argued by Hexcel (2000) that honeycomb can be manufactured with a wide range of materials such as Kevlar, aluminium, aramid, fibreglass or carbon. Honeycombs are produced by compression moulding techniques (Stocchi et al., 2014). Figure 2-3 represents an example of a honeycomb core.

Figure 2-3: Example of a honeycomb core (Stocchi et al., 2014)

Syntactic foam core

Syntactic foam is another highly considered core material in composite sandwich panels and applied in various engineering applications. Substantial research has been carried out to study the behaviour of syntactic foam cores and their applications. In comparison with metallic materials, syntactic foam core materials have many advantages such as;

lightweight, more economical, greater design freedom, and they are free from environmental effects such as corrosion (Capela et al., 2008). Syntactic foam is also considered as an excellent composite material due to its low viscosity, density and moisture absorption as well as high specific strength. In addition, it also possesses a lower conductor of electricity, and can easily be used with nailing and screwing (Lashkari and Rahmani, 2016). Figure 2-4 represents an example of a syntactic foam core sandwich panel.

Figure 2-4: Example of a syntactic foam core sandwich panel (Shawkat et al., 2008)

Syntactic foams are manufactured by mixing resin/hardener with micro-spheres. The dispersion of hollow particles with a matrix is done to obtain syntactic foam material (Lashkari and Rahmani, 2016). Typically, the production process involves mixing hollow spheres (approximately 2 μm thickness and 30-300 μm diameter) with a binder (a polymer matrix) (Shutov 1986; Kim and Ho 2000). The percentage volume fraction of micro-spheres determines the mechanical properties of syntactic foam. For example, when the volume fraction of micro-balloons is 50%, the elastic and shear modulus is 1.5 GPa and 555.6 MPa, respectively. However, when the volume fraction of micro-balloons is 19%, elastic and shear modulus are 1.9 GPa and 698.5 MPa, respectively (Capela et al., 2013). Ceramic micro-balloons are also used to fabricate aluminium matrix foam as described by Kiser et al. (1999) and Balch et al. (2005). It shows that there are not any limitations in applying only glass micro-balloons to manufacture syntactic foam materials. Syntactic foams can be produced in a variety of densities, so, it provides an option tailoring in the manufacturing process based on specific need (Lashkari and Rahmani, 2016).

2.1.5 Combining face sheets and core materials in sandwich panels

The process of combining face sheets and core materials in sandwich panels is based on the type of material used. According to Allen (1969), welding is one of the best methods if both core and face materials are metallic. However, it is not always feasible to weld metals as widely used core materials are not metallic; for example; syntactic foam as a core material. Adhesively bonded technology is one of the best options in practice to manufacture sandwich panels with syntactic foam cores. Generally, face sheets and cores are bonded together with epoxy and a hardener (Capela et al., 2013).

2.2 Application of sandwich panels

There are wide applications of composite sandwich panels in various industries such as automotive, aeronautical, civil, and others (Chandra et al., 2017). The composite sandwich panel shows superior mechanical behaviour compared to monolithic composites. The main advantage is enhanced flexural rigidity. Sandwich panels give benefits of increased stiffness and strength to weight ratio but without adding any weight. Sandwich panels performed better in terms of specific strengths compared to monolithic composites (Yan et al., 2018; Chen et al., 2018).

Usually, honeycomb, corrugated, foam and truss cores are used in composite sandwich panels. Cores with honeycomb and syntactic foam have been widely used in various applications, for example; different structures and parts in automotive industries, sporting industries and aerospace industries are built using cores with honeycomb (Rao et al., 2011; Stocchi et al., 2014; Vitale et al., 2016). Syntactic foam-based cores have been used in the construction industry as panels for cladding (Shawkat et al., 2008), bridge decks (Zoghi, 2013; Tan and Khan, 2018) and flooring in building construction (Correia et al., 2012; Chen et al., 2018). They are also used in the marine industry in various parts of the ship (Mao et al., 2018).

In the civil engineering and construction industries, the application of composite sandwich panels is ever growing. The application is widespread and used in various areas such as; bridge decks, housing constructions and buildings etc. Figure 2-5 (a) and (b) represent examples of composite sandwich applications in the bridge decks and housing construction, respectively.

(a)

(b)

(c)

Figure 2-5: Example of the application of sandwich composites (a) a footbridge using a sandwich panel in a bridge deck (b) sandwich panel as a roof and wall panels (Chen et al., 2018) (c) sandwich panel as a roof and wall panels (Tata Steel, 2017)

There is also the application of composite sandwich structures in the marine industry in various parts of ships (CORE, 2013; Mao et al., 2018). Figure 2-6 (a) represents a funnel casting with improved thermal insulation, and Figure 2-6 (b) represents a mid-ship section of a barge.

(a) (b)

Figure 2-6: Shipbuilding with steel facing and polyurethane elastomer core (a) in a funnel casting and (b) a mid-ship section of a barge. (CORE, 2013)

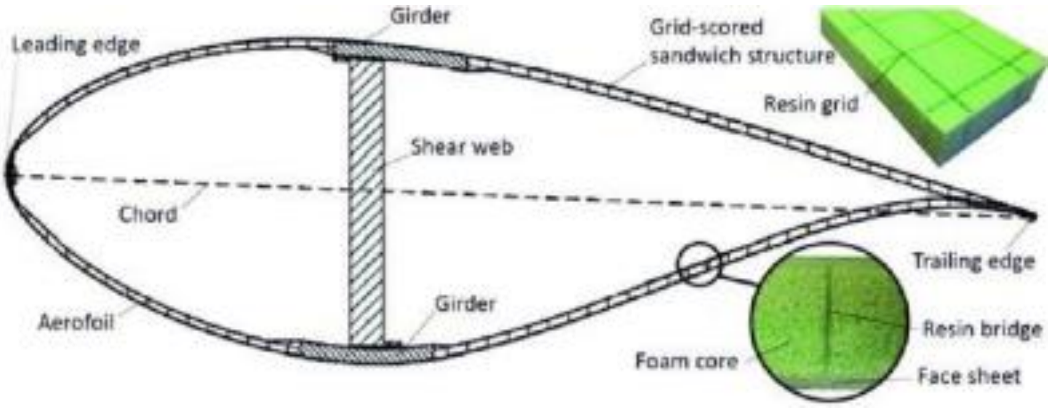

Figure 2-7: Application of a sandwich panel in a wind turbine (Laustsen et al., 2014)

Likewise, there is a broad application of composite sandwich panels in manufacturing wind turbine blades (Laustsen et al., 2014; Shah and Tarfaoui, 2017; Tan and Khan, 2018). Figure 2-7 represents the application of the sandwich structure in the wind turbine. It is argued by Shah and Tarfaoui (2017) that the extensive implementation of sandwich panels in wind turbines improves stiffness. The added stiffness helps to reduce deformations when the structure is under the aerodynamic forces (Shah and Tarfaoui, 2017).

2.3 Failure modes and failure mechanism of sandwich panels

There are various factors such as; material properties, geometry and loading conditions those play a significant role in the failure mode and the failure mechanism of sandwich panels. In sandwich panels, failure may occur within face sheets or in the core. There are five possibilities of major failure modes when a sandwich panel or beam is loaded under flexure (Dai and Hahn, 2003). Failure of the interface between the core and the face sheet, face sheet yielding, face sheet wrinkling, shear failure in the core and tension or compression failure in the core. Various failure modes and failure mechanism of face sheets are described by Hexcel (2000) that will be illustrated in a later section of this thesis.

2.3.1 Failure of face sheets

The failure of face sheets is one of the problems in sandwich panels. Commonly noted face sheets failures include; yielding of face sheets, wrinkling of face sheets, dimpling of face sheets and shear crimping (Hexcel, 2000). Figures 2-8 to 2-11 represent the failure of face sheets in different modes.

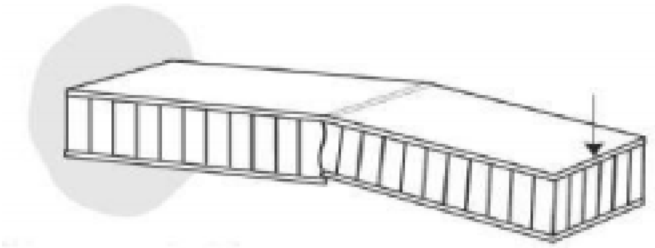

Figure 2-8: Yielding or local shear failure of the face sheets (Hexcel, 2000)

Figure 2-9: Wrinkling or local buckling of the face sheets (Hexcel,

2000)

Figure 2-10: Dimpling or rippling of the face sheets (Hexcel,

2000)

Figure 2-11: Shear crimping of the face sheets (Hexcel, 2000)

However, as mentioned earlier, the failure of face sheets is out of the scope of this research project. Therefore, it is not covered in more detail in this thesis.

2.3.2 Failure of core

There is a considerable material properties gap between the face sheet and core, causing core failure as the primary failure in composite sandwich panels (Liu et al., 2015). Generally, core materials are very weak materials compared to face sheet materials. The movement of core is restricted due to strong stiffer top and bottom laminates; hence stress is concentrated at the interface. This stress concentration is one of the big problems that cause failure in sandwich panels (Liu et al., 2015). This concentrated stress causes the failure of the sandwich panels when it reaches critical material strengths such as tensile and shear strengths. However, delamination will occur when the core material is unable to hold these concentrated stresses. The delamination and de-bonding are the leading causes of sandwich panel failures and they are usually occurred in the interface or at core due to weaker strengths and stiffness of the core material compared to face sheet material (Shah and Tarfaoui, 2017).

This failure mode can be categorized into three different forms: Mode I, Mode II and Mode III. It can also be, Mixed-Mode, Mode I and Mode II together. The fracture mode of sandwich panel cores depends upon the stiffness of the core. Figure 2-12 (a) represents opening mode. Likewise, Figures 2-12 (b) and (c) represent in-plane shearing mode and out of plane shearing mode respectively.

(a) (b) (c)

Figure 2-12: Failure modes (a) Opening- Mode I (b) In-plane shearing- Mode II (c) Out of plane shearing- Mode III (Li, 2017)

Vadakke and Carlsson (2004) carried out an experimental investigation to study the compression failure of sandwich specimens with face/core debonding. The compressive test showed that when debonding occurred due to buckling, the panel loses its loading capacity; hence the load is rapidly decreased in the post-buckling stage. There was an inverse relationship between debonding length and compressive strength. Figures 2-13 to

2-16 represent different core failures such as core debonding and core shear failure which are Mode-I and Mode II failures respectively.

Figure 2-13: Failure of core- debonding (Vadakke and Carlsson, 2004)

Figure 2-14: Failure of core- debonding (Yan et al., 2018)

Figure 2-15: Core shear failure (Yan et al., 2018)

Figure 2-16: Failure mode of the sandwich panel with a homogeneous core (Capela et al., 2013)

2.4 Improving the performance of composite sandwich panels

Various studies and research are designed to enhance the performance of composite sandwich panels. It is one of the exciting and active areas of research in academia as well as in manufacturing and construction industries. Conventional sandwich panels, manufactured with isotropic homogeneous materials, have a fracture problem in the core close to the core-face sheet interface. It is due to the high value of concentrated shear stresses near the interface region when they are exposed to different types of loadings

(Etemadi et al., 2009). They are prone to fracture in the core close to the interfaces due to mismatched material properties between the core and face sheets (Chandra et al., 2017).

One of the significant improvements under research is functionally grading of materials either in the core or in the top and bottom sheets. Functionally graded sandwich panels (FGSP) were proposed in the past few decades to mitigate those problems by reducing the gap between mismatched material properties. In FGSP, material properties are varied overall in the core or face sheets of composite sandwiches through the non-uniform distribution of material properties. FGSP requires more energy to split the sandwich panels compared to conventional sandwich panels because their failure modes are multiple fractures. Apetre et al., (2006) argued that functionally graded cores would significantly decrease the normal and shear strains whilst also reducing the deflection and magnitude of stress by eliminating discontinuity across the interface between the core and the laminates (Kashtalyan and Menshykova, 2009). In functionally grading processes, material properties are varied throughout the specified area, such as; within the core or in the face sheets. A novel sandwich panel with multi-layers in the core is proposed considering the economic aspect of syntactic foam core compared to face sheet materials, and their mechanical behaviours are studied. Improvements in the mechanical performance of composite sandwich panels are expected through this research.

2.5 Functionally graded materials (FGM) in sandwich panels

As discussed in the previous section (2.3.3), FGM is one of the options to improve the mechanical behaviour of composite sandwich panels. FGM helps to improve mechanical behaviour as well as thermal behaviour. Stresses induced in mechanical as well as thermal actions are reduced due to the variation in material properties. FGM also improve bond strengths (Liu et al., 2015).

In this thesis, a novel sandwich panel with a multi-layered core is proposed. Basically, this sandwich panel is a functionally graded sandwich panel having varied material properties in the core with multi-layers. Hence, the FGM concept, sandwich panels with FGM in the core, and their failure mechanism are reviewed in more detail in this thesis.

2.5.1 The conceptual evolution of Functionally Graded Materials

There are various shreds of evidence that the FGM concept is not new. It is argued by Suresh and Mortensen (1998) that there are different pieces of evidence of natural functionally grading of materials. Bamboo, bone and balsa wood are some of the examples (Suresh and Mortensen, 1998; Amada and Untao, 2001; Miao and Sun, 2010; Atas and Sevim, 2010).

Liu et al. (2015) mentioned that very first novel FGMs were developed by scientists from Japan in 1984. Since this time, FGMs have been manufactured using different technologies. Even though FGM is inhomogeneous in microscopic scale but on the macroscopic level, they look like a homogeneous material (Liu et al., 2015).

The functionally grading concept can be conceptualized in two different ways: stepwise or continuous graded (Udupa et al., 2014). The stepwise concept involves stepwise layers of definite thickness throughout the height of the sandwich panel. On the other hand, the continuous concept is based on the continuous change in composition and microstructure. It is argued that the continuous concept can be carried out by centrifugal force (Gasik, 2010). However, the stepwise concept is simpler and straightforward compared to the continuous concept (Udupa et al., 2014). Figure 2-17 (a) and (b) represent the continuous and stepwise material gradation scheme for functionally graded sandwich panels, respectively.

Figure 2-17: Material gradation scheme for functionally graded sandwich panel (a) Continuous (b) Stepwise (Udupa et al., 2014)

2.6 Failure mechanisms of functionally graded sandwich panels (FGSP)

The failure mechanism studies of FGSP as carried out by various researchers are critically reviewed in this section. Experimental approaches, as well as analytical solutions and numerical modelling, have been carried out by different researchers to investigate the failure mechanisms of FGSP. The findings of various research are critically reviewed.

2.6.1 Experimental tests on failure mechanism of FGSP

Various experimental tests were carried out to investigate the failure mechanisms of FGSP (Avila, 2007; Capela et al., 2013; Yan et al., 2018). Experimental research was carried out by Avila (2007) on a failure mode study of sandwich beams with a functionally graded core. *"An experimental investigation on sandwich beams with piece-wise functionally graded core was performed and compared against a conventional sandwich beam configuration* (Avila, 2007)".

(a) (b)

Figure 2-18: Failure mode and configuration of core (a) decreasing thickness from top to bottom (b) increasing thickness from top to bottom (Avila, 2007)

Four layers of different foam densities and thicknesses were bonded together with flexible adhesive. Three separate investigations were carried out. The first one with the homogeneous core, which is a conventional core. The other two specimens are arranged with the smallest material properties on the top and bottom, respectively. Thicknesses were not symmetric and varied as 2.2 mm, 3 mm, 3.8 mm and 6 mm from top to bottom and bottom to top, respectively. Bond failure in core and face sheet interface followed by shear failure were observed as shown in Figure 2-18 (Avila, 2007). This investigation concluded that the best performance of sandwich panels with FGSP could be achieved when the core layer below the top laminates has higher young's modulus. However, this test is limited to four layers in the core, and the core was not symmetric, as shown in Figure 2-18.

Figure 2-19: Failure responses of the sandwich panel having (a) Four Layers in the core (b) Homogeneous core (Capela et al., 2013)

Experimental investigations to study the failure mechanism of FGSP with homogeneous core and a four-layered syntactic foam core was carried out (Capela et al., 2013). Experimental tests were carried out by Capela et al. (2013) in examining the impact of variable densities of foam core to bending response on sandwich panels. Significant improvements were found on the performance of a four-layered sandwich panel having FGM in the core on bending stiffness and resistance compared to traditional sandwich panels having homogeneous cores. Experimental results were also compared with analytical solutions and found to be consistent, as shown in Figures 2-19 (a) and (b).

Figure 2-20: Effects of varied densities of core materials on failure response (Yan et al., 2018)

Table 2-3: Parameters of the test (Yan et al., 2018)

l	*80 mm*
H	*35 mm*
c	*15 mm*
t	*Differed*
a	*10 mm*
p	*2 mm/min*

Yan et al. (2018) carried out experimental research to investigate the effect of aluminium foam density on the failure mechanism of composite sandwich panels. The failure mechanism study of sandwich panels with a CFRP face sheet and aluminium foam core was conducted by Yan et al. (2018) under a three-point bending test method. Table 2-3 represents the parameters of the test for a schematic representation of the test set up, presented in Figure 2-20.

Figure 2-21: Effects of varied densities of core materials on failure response (Yan et al., 2018)

The strengths and stiffness of foam were increased with increased densities. The effects of the number of plies in the mechanical behaviour of composite sandwiches were also investigated. As shown in Figure 2-21, results from those investigations revealed that the influence of foam density is decreased with the increased number of plies. This investigation considered the effects of varied densities of core materials, although multi layers in the core were not considered.

Figure 2-22: Deformation process at different stages of failure response (Yan et al., 2018)

Figure 2-22 represents the deformation process at various stages of failure response in the three-point bending test. Local deformation occurred at the initial stage from point A to B, which is followed by local damage and global collapsing at B-D and D-F, respectively. At point D, the foam core collapsed. Core shear failure and interface de-bonding have been observed.

Figure 2-23: Deformation process at different stages of failure response (Yan et al., 2018)

As shown in Figure 2-23, the load-displacement curve shows the deformation process at various stages of failure response. It is corresponding to different stages, as shown in Figure 2-22. Elastic deformation occurred at the initial stage, which is linear (point O to E). The second stage is plastic deformation (point E-F) and finally, the failure stage after point F to the end.

Experimental test results are more reliable and can be used for validation of other analytical solutions and numerical modelling predictions. However, the experimental approach is expensive to investigate the failure mechanism of FGSP. From the review of various experimental tests on composite sandwich panels, it can be concluded that those experimental tests are limited to homogeneous cores or up to four layers in the core. Hence, there is still a lack of research to study the detailed failure mechanism of sandwich panels considering multi-layers, having more than four layers, in the core.

2.6.2 Predicting failure mechanisms of FGSP

Experimental methods are widely used to investigate the failure mechanism of sandwich panels, but it is quite expensive and complicated to carry out in various cases. Hence, it can be argued that it is more appropriate to carry out investigations through predictive methods in the initial stages. Nevertheless, experimental validation of numerical predictions and analytical solutions are essential. Various predictive methods are discussed in the following sections.

2.6.2.1 Predictive methods

Two predictive methods can be applied to predict the failure mechanisms of FGSP: analytical solutions and numerical modelling based on finite element analysis.

Analytical approaches

In the analytical approach, various theories based on the high order plate theory were used to predict the mechanical behaviour of composite sandwich panels having functionally graded cores (FGC). Generally, it is assumed that material properties are varied exponentially in through-thickness (Liu et al., 2015). These analytical approaches employed 3-D elasticity equations Apetre et al., (2006), third-order zig-zag models Icardi and Ferrero, (2009), polynomial equations Kashtalyan and Menshykova, (2009) and classical deflection formulas (Lashkari and Rahmani, 2016).

A simple, higher-order theory based on a shear deformation theory was developed to study the behaviour of sandwich panels Reddy (1984). Still, this study was only limited to single-layer cores of composite laminates. However, various analytical solutions were developed in the past several years for FGM.

The work carried out by Sankar (2001) consists of a beam theory that was developed to analyse a FGM beam with transverse loading conditions. The results were then compared with elasticity solutions. Stress concentrations in the beam with FGM cores were to be found less than in a homogeneous core. Displacements and stresses are obtained by solving elasticity equations (Sankar, 2001). It is argued by Sankar (2001), that elasticity equations can be used for an exact solution, but there are some limitations; such as it can only be applied in simple geometry, very specific type of loadings and boundary conditions. Likewise, analytical results were not compared with experimental results in this work.

A 3-D analytical solution for FGM was proposed by Anderson (2003). The effects of FGM on stress and displacement was performed. It was noticed that shear stress at the interface is decreased with functionally graded cores (Anderson, 2003). However, similar to Sankar (2001), analytical results were not compared with experimental results.

Likewise, an analytical model for functionally graded beams was derived by Zhu and Shankar (2004). This model was based on the Fourier series Galerkin method where polynomial functions were used to express the elastic constants in co-ordinates in through-thickness direction (Zhu and Sankar, 2004).

An analytical modelling study was also carried out to study the failure mechanism of sandwich panels with functionally graded cores (Apetre et al., 2008). Apetre et al. (2008), developed a new solution with the elasticity solution that was proposed by Sankar (2001). A new function using a polynomial expression was introduced to describe the variation of stiffness in gradation through the core thickness. However, the conclusions of both Sankar (2001) and Apetre et al. (2008) were the same. Both agreed that functionally grading of material properties decreases the interfacial stresses.

Kashtalyan and Menshykova (2009) developed a three-dimensional elastic solution for FGSP. Young’s modulus was varied exponentially throughout the thickness of the core (Kashtalyan and Menshykova, 2009). An analytical study carried out by Kashtalyan and Menshykova (2009) shows the effects of the FG core. The in-plane normal stress and shear stress at the interface between the core and the top and bottom laminate was eliminated by the FGM core when compared with a conventional single-layer core having homogeneous materials.

The bending behaviour of sandwich structures with flexible functionally graded cores based on the high-order sandwich panel theory was carried out by Lashkari and Rahmani (Lashkari and Rahmani, 2016). The results of the study were compared with a conventional single-layer core having homogeneous materials and found that there was a reduction in possible delamination between the core and face sheet interfaces (Lashkari and Rahmani, 2016). High order equations can be utilized to obtain the localised bending effects which occurred due to changes in the FGM of sandwich panels (Liu et al., 2015).

It can be seen from the literature review that there has been substantial analytical research carried out to improve the mechanical behaviour of sandwich panels by functionally grading the core materials. However, these analytical solutions are relatively complicated, applied in simple geometry, load and boundary conditions. Through these analytical approaches, the detailed failure mechanism of FGSP with multi-layers in the core in the structural level cannot be predicted accurately.

Numerical modelling

Another widely used predictive method to predict the failure mechanism of FGSP is the numerical modelling approach. Numerical modelling can be carried out using various methods such as the finite difference approach (FDA), the boundary element approach (BEA) or the finite element approach (FEA) (Becker and Karamanlidis, 2004). The basic difference between these methods is the types of elements that are applied. For example, internal cell elements are used in the finite difference method. Likewise, boundary or surface elements are used in the boundary element method, and domain elements are used in the finite element method (Becker and Karamanlidis, 2004).

In FDA, the body is separated in equal element sizes. The body is discretised into an equal and square or rectangular elements grid, hence, this approach is not applicable in curve surfaces and models with complex geometry. It is also not applicable in cases where stress concentrations are varied.

The BEA consists of separating the only boundary into a different number of elements. Line elements in 2D or surface elements in 3D modelling are used. The discretisation of a boundary is carried out into many elements where loading is applied, and shape functions are used to calculate the unknown for each element.

Likewise, in FEA, the body is discretised into a finite number of elements. Different shapes of elements can be utilised based on the problem. Different shape functions are utilized to solve the problems, and the results are re-assembled to achieve the solution for the whole problem (Becker and Karamanlidis, 2004; Liu et al., 2015). FEA is widely used to study the mechanical behaviour of sandwich panel compared to FDA and BEA. Hence, various FEA modelling and their applications to study the failure mechanism of FGSP are explored. There is very limited research considered the numerical investigation of sandwich panels with the functionally graded core. The majority of research is focused only on techniques to distribute material properties.

Vibration behaviour and the buckling of sandwich beams with functionally graded materials with a constrained viscoelastic layer using FEA were carried out by Bhangale and Ganesan (2006). Stiffness properties were varied in the through-thickness direction based on the power law. The results showed that an increased power-law index increases the critical buckling temperature (Bhangale and Ganesan, 2006).

Finite element analysis of functionally graded beams was carried out, and the results showed a maximum decreasing strain with graded cores (Etemadi et al., 2009). Numerical modelling to study the effects of free vibration characteristics of an FG beam was carried out by Alshorbagy and others (Alshorbagy et al., 2011). This investigation focused on the effects of different boundary conditions, the slenderness ratio and the power-law index (Alshorbagy et al., 2011).

2.7 Summary

There are wide applications of composite sandwich panels in various industries from aerospace to construction. However, widely used conventional sandwich panels show limited loading capacity. There is a mismatched material properties gap between laminated face sheets and the cores. Hence, they are prone to core material sliding shear fracture, interface de-bonding as well as through-thickness vertical cracking. Functionally graded sandwich panels have been proposed to improve the mechanical behaviour of conventional sandwich panels. This chapter reviewed literature related to composite sandwich panels, functionally graded materials, different types of functionally graded sandwich panels and their applications. The failure mechanism of sandwich panels and various methods such as experimental approaches, analytical solutions and numerical modelling approaches are critically reviewed. From the literature, it is found that most of the research is limited to the simplest form of sandwich panels with a homogeneous core. The following conclusions can be drawn, and research gaps are identified based on this review:

- ➢ Various studies have been carried out to improve the mechanical behaviour of sandwich panels, but they are limited to homogeneous core or with a maximum of four layers in the core;
- ➢ Analytical solutions of FGSP is limited at linear elastic stiffness; ➢ Different experimental tests were carried out, but they were limited to single-layer homogeneous cores or with a maximum of four layers in the core;
- ➢ Previously used numerical modelling and analytical approaches cannot accurately predict the detailed failure mechanism of FGSP;

- ➢ Hence, there is a clear research gap to study the detailed failure mechanism of sandwich panels having multi-layers, more than four layers, in the core; ➢ This research project will fulfil these research gaps by studying the detailed failure mechanism of sandwich panels with multi-layers, more than four layers, in the core.

Chapter 3

Methodology

3.0 Overview

In chapter 2, literature related to composite sandwich panels, functionally graded materials, different types of functionally graded sandwich panels and their applications are reviewed. It is identified that there is a wide application of composite sandwich panels with a syntactic foam core in various fields from aerospace to construction. Therefore, studying the detailed failure mechanism of composite sandwich panels with a syntactic foam core to improve mechanical behaviour has great significance.

This chapter is dedicated to the methodological aspects of this research project. Firstly, section 3.0 describes the overview, which is followed by widely used methods to predict the failure mechanism of sandwich panels in section 3.1. It discusses the detailed features of various methods such as the Cohesive Zone Model (CZM), the eXtended Finite Element Method (XFEM) and the Extended Cohesive Damage Model (ECDM), including their advantages and disadvantages. It also discusses the justification of the chosen method to predict the detailed failure mechanism of functionally graded sandwich panels (section 3.2). Secondly, the formulation of the ECDM and the ECDM modelling processes are briefly discussed in sections 3.1.3 and 3.3, respectively. Experimental data collection, the implementation of ECDM and the validation process of ECDM modelling are discussed in sections 3.4 and 3.5. Finally, the method to optimize the loading capacity

of FGSP and a method to study the geometric ratio effect on the fracture behaviour of FGSP is carried out in sections 3.6 and 3.7, respectively.

The experimental testing method is one of the most accurate and highly reliable methods to examine the detailed failure mechanism of sandwich panels. Still, they are highly time consuming and economically burdensome. Particularly, manufacturing composite sandwich panels with multi-layers in the core for experiment is another challenging issue. Hence, numerical modelling based on a finite element method is applied in this research to study the detailed failure mechanism of FGSP.

3.1 Methods to predict the failure mechanism of sandwich panels

In chapter 2, it is identified two predictive methods that can be applied to predict the failure mechanism of sandwich panels; analytical solutions and numerical modelling.

3.1.1 Analytical solutions

The analytical solution is one of the predictive methods that will give more accurate results, but they are comparatively complex. In analytical solutions, different analytical formulas are formulated based on theories to study the mechanical behaviour of sandwich panels. As discussed in chapter 2, although analytical approaches can predict more accurate results compared to numerical solutions, analytical solutions have some limitations in predicting the detailed failure mechanisms of composite sandwich panels. The currently available analytical solutions are widely applicable for sandwich panels with a homogeneous core only. They can barely predict the detailed failure mechanism of FGSP. It is noted that analytical approaches are out of the scope of this thesis.

3.1.2 Numerical modelling

Numerical modelling is another predictive method that can be used to predict the failure mechanism of sandwich panels. It is an approximation method, which is less complicated compared to analytical solutions, and it will give approximated results. Predicted results can be then compared with experimental results for validation. Numerical modelling is within the scope of this thesis, so, various numerical models with their advantages and disadvantages are explored, and the justification of the chosen method is outlined in this section. It can be argued that the numerical modelling method is one of the best approaches to predict the detailed failure mechanism of FGSP. Hence, only numerical modelling is considered in this research. There are various widely used numerical modelling methods, such as the cohesive zone model, the extended finite element method, the extended cohesive damage model and others, to predict crack behaviours in sandwich panels. However, the Extended Cohesive Damage Model (ECDM) based numerical modelling method is applied to predict the detailed failure mechanism of FGSP in this research. Justification of the chosen method is given in the later section.

Various numerical modelling approaches can be applied to predict crack behaviours of different engineering structures. However, the Cohesive Zone Model (CZM) and the eXtended Finite Element Method (XFEM) are widely used to predict failure mechanisms of sandwich panels.

3.1.2.1 Cohesive Zone Model (CZM)

The cohesive zone model, initially introduced by Barenblatt (1959), has been widely used for decades. In the cohesive zone model, the crack is regarded as two different parts; one part comprises two separate free faces and another the cohesive area (Li et al., 2019). Various aspects of CZM have also been evaluated by Elices et al., (2002a) and other researchers. This method is beneficial in the case of delamination. However, it is also applied in different various other applications. An interface element is embedded between two layers where the fractures are supposed to happen and where the traction-separation law will be used (Ghasemnejad and Aboutorabi, 2011).

Cohesive zone

Crack tip

Material 2

(a)

Interface

(b)

Figure 3-1: Illustration of Cohesive Zone Model (Rasane et al., 2018)

According to Rasane et al. (2018), a gradual failure takes place at the front of the crack tip, as shown in Figure 3-1 (a) in the CZM. The degradation will take place with the variation in material properties at the interface. Initially, two coincident points start to separate with traction within the cohesive zone. As shown in Figure 3-1 (b), two points A and B, which are coincident initially, are divided into A’ and B’. Normal traction component T_n and shear traction component T_t, as shown in Figure 3-2, are factors that will cause separation at the interface. The normal displacement component (δ_n) and the tangential displacement (δ_t) component cause movement of point A with respect to point B, as shown in Figure 3-1 (b).

Figure 3-2: Traction-separation curve in normal and tangential directions (Rasane et al., 2018)

The traction-separation behaviour can be divided into three stages: Elastic stage, Elasto plastic stage and Failure stage (Li et al., 2019). In the elastic stage, the stresses increase with an increase in displacement until reaching the maximum static force followed by relative displacement between two surfaces. In the second stage, irreversible deformation occurs due to the increase in stresses and displacement. This stage is known as Elasto plastic stage. Finally, stresses in the interface exceed the strength of interface material,

initiating the cracks in the final stage. Cracks gradually increase, expand and eventually cause damage.

However, crack propagation in composite structures may be in different arbitrary areas, but it is challenging to predict arbitrary crack propagation in composite structures through CZM (Elices et al., 2002a). CZM has been applied to investigate the fracture behaviour in various conditions by different researchers. A new analytical model based on CZM has also been proposed to predict progressive failure in a Double Cantilever Beam bonded joint, and these research findings have contributed to the decreased computational time (Cabello et al., 2017).

3.1.2.2 eXtended Finite Element Method (XFEM)

In the past few decades, based on the approach of the Partition of Unity method (PUM) Melenk and Babuska, (1996), rapid development has been made to cope with the arbitrary cracking problems in solids. Among all these PUM based approaches, the XFEM, initially introduced by Belytschko and Black (1999) is currently one of the most popular numerical tools utilized. According to Li and Chen (2016a), XFEM can thoroughly describe the strong and weak discontinuities by enriching the classical finite element approximations within the finite element framework. In XFEM, when discontinuities or crack propagations happen, there is no need to re-mesh and adapt the mesh. Additional degrees of freedom for each node are introduced to substitute the process of adapting the mesh, as shown in Figure 3-3.

Figure 3-3: The set of nodes for enrichment, the nodes enriched with Heaviside function are represented by circles (Khatir and Wahab, 2019)

The main domain or element is partitioned into sub-elements having triangular or quadrilateral properties. An accurate approximation is expected as singularity and discontinuity of elements by enrichment (Belytschko et al., 2009). For more than a decade the crack behaviours of materials are described using *“the classical piecewise polynomial approximation basis within the finite element framework”* (Li and Chen, 2016a) pg-1. Currently, XFEM has already been available in commercial FEM software, such as Abaqus.

3.1.2.3 Extended Cohesive Damage Model (ECDM)

Various research investigations have been conducted, and refinements carried out based on XFEM and CZM. However, a different approach to overcome the problems related to CZM and XFEM has been developed by Chen (2014) to analyse the fracture behaviour of adhesively bonded joints. In this investigation, ECDM has supplied efficient and effective modelling techniques for adhesive and cohesive damage analysis. ECDM has been applied through a User-defined Element Library (UEL) to predict the failure mechanism in the interface and successfully validated the effectiveness of ECDM.

According to research carried out by Li & Chen (2015), ECDM has been efficiently able to capture the failure mechanism of composite structures with much less computational time regardless of the known location of the crack and its predefined path as shown in Figure 3-4. It is a significant numerical and analytical challenge to determine the evolving crack boundaries and deformation fields, which represent a highly nonlinear system. A novel model, ECDM, developed by Li & Chen (2015) has been provided with evidence as an efficient and effective tool to investigate the multi-crack failure mechanism in fibre composites in a two-dimensional domain.

Figure 3-4: The ECDM simulated delamination migration together with a matrix crack (Li and Chen, 2015)

Based on the research carried out by Oliver, Huespe, & Sanchez (2006), computational efficiency can be improved with the elimination of enriched degrees of freedom (DoFs). Hence, additional degrees of freedoms in XFEM are eliminated and embedded with CDM in ECDM.

It is challenging to predict the detailed fracture mechanisms of composite sandwich panels, particularly FGSP with multi-layered cores due to their complex failure modes, different types of cracks as well as unknown fracture paths. There are two different approaches, e.g. the cohesive zone model (CZM) (Elices et al., 2002b; Blackman et al., 2003) and the extended finite element method (XFEM) Swati et al., (2017), which have been in practice for decades in the prediction of discontinuities in various structures. These techniques have some shortfalls due to their limited functions and features. For example, CZM needs prior defined crack paths and a large amount of computational work in a nonlinear iteration. In addition, it often meets convergence problems in simulating crack propagation at the structural level.

Likewise, the current XFEM has a limited special function in defining the displacement field at the crack front; it can predict a single type of crack. This method needs considerable CPU time because of an additional enriched degree of freedoms used for discontinuities (Li and Chen, 2015; Li and Chen, 2017a). Oliver et al., (2003) investigated an embedded finite element method (E-FEM) which has an implementation of elemental enrichments rather than the nodal enrichments required by XFEM to improve accuracy.

Another elemental enrichment method to improve accuracy in discontinuities is a variational multiscale cohesive method (VMCM) (Rudraraju et al., 2012). Lin et al. (2019) developed a continuum de-cohesive finite element (CDFE). It has similarities to the method of extended cohesive damage model (ECDM) developed by Li & Chen (Li and Chen, 2015; Li and Chen, 2016; Li and Chen, 2017a; Li and Chen, 2017b; Li and Chen, 2017c). Both CDFE and ECDM have an implementation of enrichments at an elemental level, unlike E-FEM and VMCM; fully condensed equilibrium equations are applied to improve efficiency. In both CDFE and ECDM, introduced enriched DOFs are condensed into an equivalent stiffness matrix such that the methods can be implemented into the standard FEM framework to improve the computational efficiency. Moreover, the crack initiation and propagation in both methods are based on cohesive crack growth.

The major difference between the two methods is stated as follows. On a methodological level, CDFE is inspired by VMCM while the ECDM is motivated by XFEM. In CDFE, a cohesive crack is physically introduced into the element while in ECDM, like XFEM, the crack is represented by enriched DOFs without being physically inserted into the element. In this way, the partition of unity (POU) in CDFE is for cohesive crack insertion, while that in ECDM is solely for numerical integration in sub-domains. In addition, due to this difference, the damage factor in CDFE is based upon the physical crack separation, through the traction-separation law. In contrast, in ECDM, the cohesive law is related to the strain field. On a numerical implementation level, the current CDFE is developed within an explicit framework, using Abaqus subroutine VUEL. The ECDM is developed within an implicit framework with significant accuracy and efficiency, using Abaqus subroutine UEL.

In ECDM formulations, enriched DOFs are condensed after crack initiation, and the crack opening follows the cohesive behaviour without the crack-tip enrichment in XFEM for singular crack-tip stress distributions. After condensation, an equivalent stiffness matrix is obtained such that the method can be implemented with standard FEM codes (Li and Chen, 20165; Li and Chen, 2016; Li and Chen, 2017a; Li and Chen, 2017b; Li and Chen, 2017c). Various problems of composite materials have been studied with ECDM (Li and Chen, 2017b; Li and Chen, 2017c). That including fracture benchmark specimens, four point bending of a stiffened laminated composite panel, crack propagation in a composite T-joint, and delamination migration in composite beams.

Through the studied examples, the effectiveness, robustness and efficiency of the method have been shown. ECDM reduces the CPU time of prediction by more than 90% and 60% compared to CZM and XFEM, respectively based on the same investigated specimens (Li and Chen, 2017b; Li and Chen, 2017c). Unlike CZM, pre-defined crack paths are no

longer required by ECDM and ECDM has no convergence problems in nonlinear fracture analysis of investigated composite samples (Li and Chen, 2015; Li and Chen, 2016; Li and Chen, 2017c).

Furthermore, to resolve these problems with CZM and XFEM; theoretical formulation of ECDM has been further developed, and a derivation has been derived to form a basic equilibrium equation through ECDM. According to Li & Chen (2015), the extended cohesive damage model has been derived within the framework of XFEM, where crack tip singularity has not been accounted for. Fang, Yang, Cox, & Zhou (2011) argued that the result would not be influenced by ignoring the crack-tip singularity while the cracks are propagating, and the numerical efficiency can be improved significantly.

3.1.3 Brief ECDM formulation

A user element model based on the commercial package ABAQUS is used to apply ECDM in the non-linear failure analysis to investigate the fracture behaviour of FGSP. Basic theoretical ECDM formulas that are implemented in an ECDM 2D 4-node quadrilateral element is described below.

It is argued by Belytschko and Black (1999) that partition of unity condition can be satisfied by a 2D quadrilateral 4-node element with classical shape functions N_i (i=1, 2, 3, 4). Hence, the displacement approximation can be presented, as shown in Eq. (1).

$$\begin{Bmatrix}u(\xi,\eta)\\v(\xi,\eta)\end{Bmatrix}=\sum_{i=1}^{4}N_i(\xi,\eta)\begin{Bmatrix}u_i\\v_i\end{Bmatrix}+step(\xi,\eta)\sum_{i=1}^{4}N_i(\xi,\eta)\begin{Bmatrix}u_i^1\\v_i^1\end{Bmatrix} \quad (1)$$

where u and v represent displacement in x and y directions respectively. In addition, step function can be expressed as:

( ) ( ) ( ) $_i n\ H\ n\ H\ _i n_i$

$step_{d\ d}$

ξ, ξ, ξ ,

= Γ− Γ (2)

According to Li and Chen (2017c), the shape function matrices **N** and the discretised gradient operator matrix **B** are established in general FEM format.

[ ] [ ] STD ENR **N** = **N** ,**N** (3) Where standard function - **N**STD and enriched function - **N**ENR can be represented as:

| ⌊ ⌈ N 0 N 0 N 0 N 0 | ⌋ ⌉

1 3 2 4

N (4)

=

STD **N**

0 N 1 0 N 2 0 N 3 0 4

step N 0 step N

1 1 step N 4 4

0 3 3 0

| ⌊ ⌈ step N 0 | ⌋ ⌉

2 2

N(5)

=

ENR step N

0 1 step N 2 0 3

step N 1 0 2 step N 3 0 4 4

According to Li and Chen (2017c), the formulation of ECDM is lower-order compared to XFEM, and only standard degrees of freedoms are used for nodal displacement in ECDM to represent discontinuities in cracked elements. Based on the weak form of equilibrium equation by the Bubnov-Galerkin method, the discrete form of the final equilibrium equation for static analysis can be represented as:

$(( )) ( )$ *coh*

$-1 \; -1$

u u u a a a a u **K K K K** *u* **f K K f**

u u a a a

$- = -$ (6)

ext

where u represents displacement due to standard degrees of freedom, matrices $\mathbf{K}^{uu}$ and $\mathbf{K}^{aa}$ represent a standard and enriched approximation, respectively. Likewise, $\mathbf{K}^{ua}$ and $\mathbf{K}^{au}$ represent coupled standard and enriched FE approximations; $\mathbf{f}^{u}_{ext}$is for equivalent nodal force vector due to standard FEM degrees of freedom. Calculations for $\mathbf{K}^{uu}$, $\mathbf{K}^{aa}$, $\mathbf{K}^{ua}$ and $\mathbf{K}^{au}$ are given below.

$\int \int$

K B DB B DB $^{uu} = \Omega + \Omega$

d d

STD STD STD STD

$+ -$

$\Omega \; \Omega$

e e

au

$\int \int$

K B DB B DB

$= \Omega + \Omega$

d d

ENR STD ENR STD

$+ -$

$\Omega \; \Omega$

(7)

u a

e e $\int \int$

K B DB B DB $= \Omega + \Omega$

d d

STD ENR STD ENR

$+ -$

$\Omega \; \Omega$

e e

aa

$\int \int$

K B DB B DB

$= \Omega + \Omega$

d d

ENR ENR ENR ENR

$+ -$

$\Omega \; \Omega$

e e

Where the gradient matrices **B** for a 2D quadrilateral element can be expressed as:

$[\;] \; [\;]$ STD ENR **B** = **B** ,**B** (8) Where $\mathbf{B}_{STD}$ and $\mathbf{B}_{ENR}$ can be calculated by Equations.

9 and 10.

$$0$$

| | | ⎦ ⎤

| | | ⎣ N N

⎡ $_{i\,x\,,}$

$$\mathbf{B}^{0}\quad(9)$$

$^{\mathrm{STD}}$ $=$ $N\,N$ $_{i\,y\,,}$

$_{i\,y\,i\,x}$
$_{,\,,}$

0

step N step N +

| | | ⎣ ⎡ + ++ | | | ⎦ ⎤

i i,x i,x i 0

step N step N

B (10)

ENR
=

i i,y i,y i

step N step N step N step
N i i,y i,y i i i,x i,x i

Likewise, Equation 11 can express $\mathbf{f}_{\mathrm{coh}}$, internal nodal force vector due to cohesive traction, which will be applied in the crack surface, as shown in Figure 3-5.

$$\int_{\Gamma}$$

$$\mathbf{f}_{coh}\ \mathbf{N}_{\mathrm{STD}}\mathbf{t}d\quad(11)$$

$$=_{Crack}\Gamma_{Element}$$

In which, **t** represents traction between two crack surfaces on a cracked element

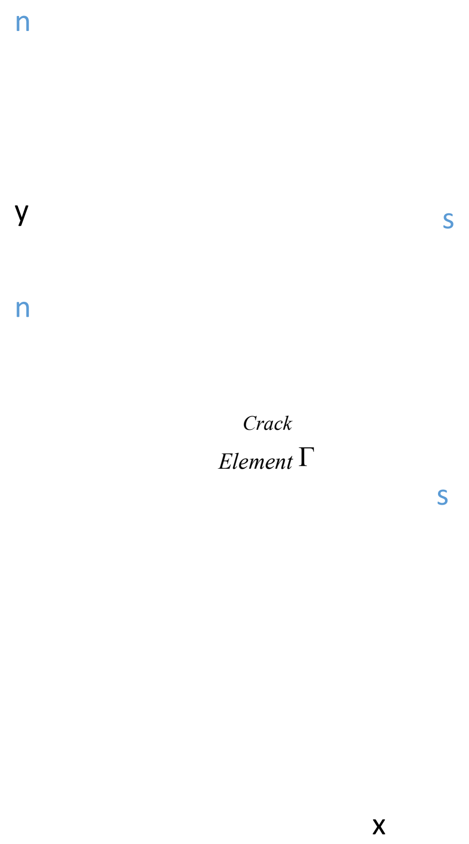

Figure 3-5: Cohesive tractions between cracked surfaces

In this investigation, a mixed-mode failure criterion is also considered. The Benzeggagh and Kenane law, which is also known as B-K law for mixed-mode failure, considers total fracture energy as a function of the crack mode ratio. It was found that B-K criteria can be regarded as a more reliable failure criterion for the mixed-mode failure of epoxy composites. According to Reeder (2006), the following expression can be used as 3D mixed-mode failure criteria:

$$\frac{G_T}{\left(G_{IC} + (G_{IIC} - G_{IC})(G_{II}/G_T) + (G_{IIIC} - G_{IC})(G_{III}/G_T)\right)\left((G_{II} + G_{III})/G_T\right)^{n-1}} \geq 1 \qquad (12)$$

Where, G_T is the total energy release rate which is equivalent to G_I+ G_{II} + G_{III} and accounted for as a function of the ratio (G_{II} + G_{III})/G_T. Likewise, G_{IC}, G_{IIC} and G_{III} are opening and two shear fracture energies, respectively, and n is the power fraction parameter.

In 2D case $G_{III} = 0$, so, it is equivalent to B-K criteria (Benzeggagh and Kenane, 1996) as given in Equation- 13 for 2D cases:

$$\frac{G_T}{G_{IC} + (G_{IIC} - G_{IC})(G_{II}/G_T)^n} \ge 1 \qquad (13)$$

3.2 Methodology choice and limitations of other methods

There are very complex failure mechanisms of composite structures, which are still not resolved by various modelling approaches for damage mechanics. Various refinements on CZM and XFEM have been carried out (Xiao and Karihaloo, 2006; Fries and Belytschko, 2010) and others. However, both modelling techniques have shortfalls, such as the special mesh treatment required by CZM and the convergence when encountering multiple crack propagation, which is hard to achieve (Li and Chen, 2015). CZM also needs high computational time, fine mesh (Cabello et al., 2017) and requires known prior crack paths, which are hard to define in composite structures for multi cracks (Li and Chen, 2016a). Likewise, XFEM needs high computational time when it encounters strong discontinuity due to additional degrees of freedom (Li and Chen, 2015). There have been significant improvements which have been happening since then to simulates the strong discontinuity problem. In this research, ECDM, the model developed by Li and Chen (2015) is implemented to investigate the detailed failure mechanism of FGSP due to the following attributes of ECDM:

- Elimination of enriched degrees of freedoms and embedded with a cohesive damage model at the ECDM element level;

- Improved computational efficiency by 90% and 60% compared to CZM and XFEM respectively;
- No pre-prepared prior crack path needed;
- Able to simulate multi-crack propagation;
- No significant nonlinear iteration failure problems identified.

3.3 ECDM modelling procedure in ABAQUS

One of the applications of FEM is an analysis of civil engineering structures. Various commercial software programs such as LUSAS, ABAQUS, LS-DYNA, ANSYS, MSC NASTRAN, etc. have been developed based on FEM for structural analysis. However, ABAQUS is one of the most highly efficient software packages for computer-aided engineering problems and analysis. It is based on the finite element and can be used to investigate the multiple crack evolution in laminated composites due to the following reasons:

- ABAQUS is a finite element software, quite straightforward, that is supported by Dassault and is widely used in academic and engineering research.
- ABAQUS contains various non-linear solver, standard element library and different solvers for solving non-linearity.
- Element types that are available in ABAQUS mostly meet the general requirements (ABAQUS, 2014).
- ABAQUS facilitates the user to define their own subroutines such as UEL where the user can define specific elements with variable constitutions.

3.3.1 ECDM modelling procedure

As shown in Figure 3-6, the ECDM modelling procedure comprises five different stages from the creation of geometry to the final output as follows:

1. Create geometry in ABAQUS;
2. Develop the ECDM elements by creating a new mesh with same model definitions (doubly meshes);
3. Develop new input data file (INP) with the user-defined elements of ECDM;
4. Run through ABAQUS non-linear solver;
5. Solved by ECDM based modelling and transferred into showing mesh for visualisation

Figure 3-6: ECDM modelling procedure

In this investigation, a 2D ECDM subroutine has been used and applied in various cases which further verifies the efficiency of 2D ECDM. Several models have been created. Some of them worked very well, whilst some of them did not. Therefore, continuous refinement has been carried out to achieve acceptable results.

In the application of ECDM, an input (INP) data file created through ABAQUS CAE is used to develop a new INP data file which will run through the ABAQUS command by calling a user-defined UEL subroutine (For example, ***ABAQUS Job****=Job name* followed by ***user****=user defined UEL subroutine).* While developing a new INP data file to apply ECDM, it is essential to follow the various sequential steps.

Doubly meshing technology

One of the distinguishing features of ECDM modelling is doubly meshing technology. This technology has never been used in any other methods. The process includes