Structural Behavior of Adhesively Bonded High Density Polyethylene Composite Beams

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THESIS
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Aiman Shibli
CONTRIBUTION OF THE AUTHORS

Chapters 5 represent one published manuscript of which I was the primary author of the conference paper (Shibli A, Issa M. Structural Adhesive Behavior – Experimental and Computational Study. Conference on Reliable Engineering Computing on May 26th 2014). My advisor, Professor Mohsen A. Issa was primarily involved in all the phases of the research paper.
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ABSTRACT

Finding a sustainable and structural material for the civil infrastructure domain, while remaining financially feasible, is a challenge for engineers. Recycled Plastic Lumber (RPL) is identified as an excellent sustainable material used by the construction industry in non-load bearing applications. There is a demand and an opportunity to resolve the aforementioned challenge by migrating RPL into structural applications. Although RPL has significant sustainable and structural advantages, such as light weight, low cost and high resistance to environmental degradation, its usability in the civil infrastructure applications is still at its early stages due to a lack of design guidelines. Furthermore, due to the brittleness of the RPL material, joining RPL components impose another challenge for engineers. Recently, however, many structural industries have considered adhesive binding as an excellent candidate for replacing the traditional joining methods (e.g. bolting and riveting) for joining load-bearing components, especially for scenarios involving joining brittle materials such RPL. The attractiveness of adhesives stems from their unique combinations of properties, which include: high strength, light weight, dimensional stability, high resistance to environmental degradation and ease of use. Due to these unique characteristics and advantages, the use of adhesive joints is on the rise in structural applications. On the other hand, the traditional bolted joint methods have gone a long way in creating appropriate technologies and gained years of design experience, which cannot be easily replaced. Accordingly, switching from traditional joining methods to adhesive bonding in civil infrastructure applications requires a large investment to establish a level of understanding comparable to that associated with traditional joining methods. In particular,
it is crucial to characterize and fully understand bonded joint behaviors, strength and failure properties, and to be able to predict them for given geometries and loads.

This research addresses both challenges by providing design guidelines for utilizing RPL in load-bearing structural application and by fully characterizing the behavior of adhesively bonded RPL joints. For addressing the first challenge, this research covers structural and sustainability assessments of an RPL beam. Experimental and numerical results of the four-point bending structural assessment of RPL beams reinforced with Glass Fiber Reinforced Polymer (GFRP) indicate that as the amount of GFRP reinforcement area increases, the stiffness of the RPL increases up to four times linearly. The results also indicate that optimizing the beam section by using an I-shape beam or a hollow beam can reduce the weight and increase the surface area, improving the heat treatment process while maintaining 90%-95% of the beam stiffness. Results of the three pillars of the sustainability assessment (environmental, economic, and social) show that reinforced recycled plastic beams have great environmental benefits compared to other structural materials, such as the reinforced concrete and the wood beams.

For addressing the second challenge, this research covers the following: i) investigating the behavior of structural adhesives by characterizing their mechanical properties, ii) investigating the failure limits and failure modes of structural adhesives and iii) establishing a representative material model that can mimic their behavior and can be used in numerical models for computational studies. Comparison between experimental results and numerical results obtained from 3D finite element analysis show that the produced material model does mimic the actual behavior of the adhesive material at the bulk level and the interface level.
1. INTRODUCTION

1.1. **Background**

1.1.1. **Material in infrastructure domain**

Finding new structural materials that combine sustainability, durability and being environmentally friendly while remaining financially feasible is a challenge for engineers. The most used structural materials are mainly made of reinforced concrete, steel and timber. These structural materials have limitations, such as corrosion of steel and rotting of timber, which drive engineers to look for better performing materials. While scientists and engineers are trying to introduce new robust structural materials for the infrastructure domain, they are also trying to solve environmental issues such as reducing the volume of recycled plastic in landfills.

Disposal of waste materials becomes difficult for management authorities, since special precautions are required to avoid emission of toxic gases and liquids. According to Krishnaswamy and Lampo (2001), the volume of plastics in landfills reaches almost twenty-five percent of the total volume. Integrating recycled plastic, by substituting it for wood in some structural applications, will have major benefits to the environment through reducing the municipal solid waste at landfill sites.

Recycled Plastic Lumber (RPL) consumes large quantities of waste plastics that would otherwise be sent to landfills. RPL is typically used in picnic furniture, playground equipment, landscaping tiles, privacy fences, industrial cushioning, guardrails, telephone poles, railroad tiles, marine structures, deck planks, and other fresh and salt-water shoreline applications. So far, RPL is used in non-structural applications that do not require critical load-bearing. The demand for such non-structural products using recycled plastics has been
growing every year but they have been fairly limited by their end-use applications. Improving and developing RPL material properties to be used in structural applications, such as bridges and decks, provide new growth opportunities that help continuously divert more volumes of plastic waste from the landfills. RPL can be made in many different ways, mainly out of high density polyethylene (HDPE). Post-consumer bottles (e.g. plastic milk and detergent bottles) are good sources for HDPE-RPL.

Historically, plastic lumber has cost more than wood alternatives on a per linear foot basis. Recently, with the increased scrutiny of treated lumber and the limited availability of hardwood, plastic lumber has become a more economical option. The following features are some of the advantages of RPL over wood:

- Exceptional resistance to moisture, fading, insects, splinting, warping and other hazards associated with exposure of wood products to the environment.
- Does not need waterproofing or staining.
- UV inhibitors protect it from environmental exposure and maintain color stability.
- Has the ability to retain its new look for years and does not fade except slightly over its entire service life.
Current concerns regarding the use of RPL products in structural applications include low stiffness and low density, which can result in unfavorable conditions under service loads. The ability to overcome these limitations by improving RPL stiffness and strength addresses the historical concerns and opens up significant new markets in structural applications. Using additives and embedded structural elements produces higher strength and stiffer recycled plastic composites. In addition, the stiffness can be further improved by reinforcing RPL beams with fiberglass rods.

1.1.2. Joints in infrastructure domain

Civil infrastructure applications have been increasingly using Fiber-reinforced polymer (FRP) composites due to their advantageous material properties, such as their high strength, high stiffness, light weight, high resistance to environmental degradation and rapid installation. However, structural FRP components are difficult to connect using bolted joints due to the brittleness of this material. The current traditional joining methods such as bolting and riveting create stress concentrations which lead to premature failure. Furthermore, holes in the bolted joints are areas for stress concentrations and moisture ingress, which can impact the overall structure durability. Many structural industries have considered utilizing adhesives for joining load-bearing components as an excellent candidate for replacing the traditional bolted joint methods. They have been attracted to use adhesives due to several reasons:

- High joint efficiency and dimensional stability
- Adhesive distribute load across the entire joint area
- Fewer stress concentrations
- No need to dig holes and damage the adherends; holes are points where moisture ingress can occur, which can affect durability

- Low structural weight

- Low fabrication cost and improved damage tolerance

- Rot resistance

- Ease of use

The traditional bolted joint methods have gone a long way in creating appropriate technologies and gained years of design experience, which cannot be easily replaced. Switching from traditional joining methods to adhesives bonding in the civil infrastructure applications requires a large investment. Currently adhesive joints for civil infrastructure applications are in its infancy due to the lack of design guidelines and consistent specifications. Although adhesive bonding has been studied and used widely in the fields of aerospace and automotive, these studies cannot be directly transferred to the civil infrastructure domain. Adhesive bonding for civil structural application have essential differences with respect to type of materials, loadings, geometries and environmental conditions.

1.2. Objectives

The overall goal of this study is to contribute to the development of practical and reliable design methods for HDPE composite beams and structural adhesive into the infrastructure application domain.

Recycled Plastic lumber (RPL) is an environmentally friendly material, which has been identified as a potential material for structural applications. RPL is already known as
the best way of recycling high density polyethylene (HDPE) generated by post-consumer plastic containers collected in recycling programs. This study focuses on the technical and sustainability assessment of recycled plastic beams for structural applications:

- In the technical assessment, a numerical study will be conducted to investigate the flexural behavior of recycled plastic beams reinforced with Glass Fiber Reinforced Polymer (GFRP) bars under virtual four-point bend test using finite element methods. The numerical results will be compared with reinforced concrete beam and wood beams experimental test data to determine whether recycled plastic reinforced beam can be designed to meet the same technical requirements as reinforced concrete beams and wood beams.

- In the sustainability assessment, three different short span beam types will be evaluated: reinforced recycled plastic beam, reinforced concrete beam and wood beam. Assessments of the three sustainability pillars will be performed: environmental assessment, economic assessment and social assessment.

Recycled Plastic lumber RPL has been used by the construction industry in non-load bearing applications, however there is a recent demand and effort to migrate RPL into structural applications such as marine fenders, decking for residential and commercial uses, small span bridges, and other fresh and salt water shoreline applications. Although RPL has significant potential and advantages such as light weight, low cost and high resistance to environmental degradation, its usability in the civil infrastructure applications is still at an early stage due to a lack of design guidelines and consistent specifications. Usually plastic lumber is not homogeneous across its entire cross section. The inside core is a foam-like material and typically lighter than the outside perimeter which is a hard skin. Therefore, it is
not possible to determine the tensile strength by molding the RPL into a shape of a “dogbone” and tension testing like other materials. Testing the structural behavior of larger sizes or actual structural elements such as RPL beams is important to develop the specifications and guidelines for designing structures. This experimental and numerical study aim to investigate the flexural behavior of plastic lumber beams reinforced with Glass Fiber Reinforced Polymer (GFRP) bars. The parameters of the study are cross-sectional area of the GFRP, cross sectional area of the beam, span length and recycled plastic mix.

Due to the brittleness of the RPL material, joining RPL components impose another challenge for engineers. Recently, however, many structural industries have considered adhesive binding as an excellent candidate for replacing the traditional joining methods (e.g. bolting and riveting) for joining load-bearing components, especially for scenarios involving joining brittle materials such RPL. The attractiveness of adhesives stems from their unique combination of properties, which include: high strength, light-weight, dimensional stability, high resistance to environmental degradation and ease of use.

The traditional bolted joint methods have gone a long way in creating appropriate technologies and have gained years of design experience, which cannot be easily replaced. Accordingly, switching from traditional joining methods to adhesives bonding in civil infrastructure applications requires a large investment to establish a level of understanding comparable to that associated with the traditional joining methods. One of the important steps towards greater use of structural adhesives in civil structural applications is investigating the behavior of structural adhesives in order to be able to utilize them in infrastructure applications. The present study was undertaken to investigate the bonded joint behavior, strength and failure limits. The objectives of this part of the study are as follow:
• Investigating the behavior of structural adhesives by characterizing their mechanical properties,

• Investigating the failure limits and failure modes of structural adhesives and

• Establishing a representative material model that can mimic the behavior of the structural adhesives and can be used in numerical models for computational studies.
2. LITERATURE REVIEW

2.1. Introduction

It is an era of ‘Going Green’ and striving to build a sustainable society. An important aspect of sustainability in the infrastructure domain is to give existing materials new life by reusing and recycling them. In order to build environmentally friendly structures, we must answer all the technical requirements and remain financially feasible, resulting in big challenges for engineers. Our planet is full of environmentally friendly structural materials that can replace existing traditional structural materials and our responsibility is to investigate these materials and integrate them into the infrastructure domain to build echo-friendly, reliable and economical structures.

Plastics production has been increasing exponentially for the past six decades. Worldwide and European plastic production increased from 1.5 million tons in 1950 to 265 million tons in 2011 (PlasticsEurope, 2011). The volume of plastics in landfills reached almost 25% of the total volume (Krishnaswamy and Lampo, 2001). Recycled plastic appear to be a promising way to answer future plastics demands and to help reducing plastics in landfills (Ehrig, 1992). Recycled Plastic lumber (RPL) is an environmentally friendly material that has been identified as a potential material for structural applications. RPL is known as the best way of recycling high density polyethylene (HDPE) generated by post-consumer plastic containers collected in recycling programs.

RPL has been used by the construction industry in several non-load bearing applications; however, there is a recent demand and efforts to migrate RPL into structural applications. Such applications include marine fenders, decking for residential and commercial uses, small span bridges, and other fresh and salt water shoreline applications.
RPL has significant potential and advantages such as light weight, low cost and high resistance to environmental degradation.

RPL material is known as brittle material which makes joining RPL components a challenge for engineers. Recently, however, many structural industries have considered adhesive binding as an excellent candidate for replacing the traditional joining methods (e.g. bolting and riveting) for joining load-bearing components, especially for scenarios involving joining brittle materials such RPL. The attractiveness of adhesives stems from their unique combinations of properties which include; high strength, light weight, dimensional stability, ease of use, uniform loading without stress concentrations, high resistance to environmental degradation, and rapid installation.

Structural adhesives have been around for a long time. They have been made from plants and animals up until the 19th century; however in the 20th century synthetic chemicals have taken over. Adhesives have been used in all types of manufacturing: clothing, shoes, aerospace, automobile, and even human tissues. Adhesive bonding is used as a mean to join different parts together; it has been increasingly used in constructions of aircraft and automobile as a replacement of traditional joining methods such bolting, riveting and spot-welding.

Adhesive bonding is still in its infancy in civil infrastructure applications due to the lack of design guidelines and consistent specifications. Although it has been studied and widely used in the fields of aerospace and automotive, these studies cannot be directly transferred to the civil infrastructure domain. Adhesive bonding for civil structural application have essential differences with respect to type of materials, loadings, geometries and environmental conditions.
The traditional bolted joint methods in civil infrastructure applications have gone a long way in creating appropriate technologies and gained years of design experience, which cannot be easily replaced. Switching from traditional joining methods to adhesives bonding in civil infrastructure applications requires a large investment to establish a level of understanding comparable to that associated with traditional joining methods. In particular, it is crucial to characterize and fully understand bonded joint behavior, strength and failure properties, and to be able to predict them for a given geometries and loads.

There are several studies on structurally adhesive joints. Most of these studies follow the same two assumptions. The first of which is that structural adhesives behave elastically linear. The second of which is that structural adhesives always fail cohesively. Buyukozturk pointed out that more realistic assumptions are needed to provide better approximations of joint strength and behavior (Buyukozturk et al, 2004). Haghani studied the adhesive joints which are used to bond CFRP laminates to steel substrate using experimental and numerical approaches (Haghani, 2010). He concluded that non-linear deformation of an adhesive can contribute to a redistribution of strain and joint capacity.

Utilizing adhesive bonding in civil infrastructure applications does not only replace the traditional joining methods of bolting and riveting, but also opens the door for using new structural materials such reinforced polymers (FRP) composites, recycled plastic materials and other new composites. These newly proposed structural materials are brittle and cannot be joined using traditional joining methods, which create stress concentrations and lead to premature failures. Furthermore, holes in the bolted joints are areas for stress concentrations and moisture ingress, which can impact the overall structure durability. Adhesive joints are
excellent candidate to replace traditional joining methods in these scenarios. They lead to uniform loading without stress concentrations and without moisture ingress.

2.2. Background

- Basic Properties of Adhesives

  A definition of an adhesive is a material which can be applied between two surfaces of materials to join them together and prevent separation. An adhesive must wet to the substrate surface in order to make proper contact, and then it must harden to a cohesively strong solid in order to resist separation.

  There are basic terms that should be known when dealing with adhesives such as shelf-life and pot-life:

  - Shelf-life: is the time that adhesive can be stored before use
  - Pot-life: is the maximum allowed time between adhesive mixing and application

- Basic Chemistry of Adhesives

  Adhesives are polymers which can have linear, branched or cross-linked chains as shown in Figure 2-1:

  ![Linear, Branched, Cross-linked Adhesives](image-url)
Figure 2-1. Linear, branched and cross-linked structures of polymers.

Linear and branched polymers have similar properties; they flow at high temperatures and dissolve with the use of solvents. Cross-linked polymers do not flow at high temperatures and do not dissolve. Structural adhesives are cross-linked polymers.

Various adhesives contain additives that are not polymers to enhance the adhesive’s properties. The following are some of the widely used types additives and the role they play:

- Stabilizer additive to resist degradation,
- Plasticizer additive to lower the glass transition temperature and increase flexibility
- Powder mineral fillers to reduce shrinkage

Polymerization

Polymerization is the joining of individual monomers to form a polymer. Monomers can combine straight, branched or cross-linked polymer as shown in Figure 2-1. These different polymer structures have different mechanical properties.

- Thermoplastics: Polymers with straight and branched chains are thermoplastics. They soften and liquefy under heat, and solidify under cooling.
- Thermoset materials: Polymers with cross-linked chains are thermosets. They do not melt under heat since their chain segments are strong bonded, chemically. The chemical bond is demonstrated in black dot in Figure 2-2.
The mechanical behavior of thermoplastics and thermoset materials are different. The schematic in Figure 2-3 shows polymers behavior at increasing temperature.

Figure 2-2. Thermoplastic and thermoset polymer structures.

Figure 2-3. Polymer state of thermoplastic and thermoset at increasing temperature.
Glass Transition Temperature

Understanding the behavior of polymer under the influence of temperature is important as it indicates different mechanical behaviors and stiffness values of the polymer. Below glass temperature (Tg), the polymers have high stiffness values. These values decrease when the glass temperature is exceeded because of the increasing mobility of the molecules at higher temperatures.
3. SUSTAINABILITY ASSESSMENT OF HDPE COMPOSITE BEAMS

3.1. Introduction

It is an era of ‘Going Green’ and striving to build a sustainable society. An important aspect of sustainability in the infrastructure domain is to give existing materials new life by reusing and recycling them. In order to build environmentally friendly structures, we must answer all the technical requirements and remain financially feasible, resulting in big challenges for engineers. Our planet is full of environmentally friendly structural materials that can replace existing traditional structural materials and our responsibility is to investigate these materials and integrate them into the infrastructure domain to build eco-friendly, reliable and economical structures.

Recycled plastic lumber (RPL) is an environmentally friendly material that has been identified as a potential material for structural applications. RPL is known as the best way of recycling high density polyethylene (HDPE) generated by post-consumer plastic containers collected in recycling programs. This study focuses on technical and sustainability assessment of recycled plastic beam for structural applications.

In the technical assessment, a numerical study was conducted to investigate the flexural behavior of recycled plastic beams reinforced with Glass Fiber Reinforced Polymer (GFRP) bars. This assessment employed the finite element methods to evaluate the flexural behavior of PRL beams using a four-point bending configuration. The numerical results were compared with the experimental test data of reinforced concrete beams and wooden beams to determine whether recycled plastic reinforced beams can be designed to meet the same technical requirements as reinforced concrete beams and wooden beams.
In the sustainability assessment, three different short span beam types were evaluated: reinforced recycled plastic beams, reinforced concrete beam and wooden beams. Assessments of the three sustainability pillars were performed; i.e. environmental assessment, economic assessment and social assessment.

3.2. Technical Assessment

The main challenge of recycled plastic products is their low stiffness which can result in unfavorable conditions under service loads. Therefore, the ability to improve stiffness and strength addressed these concerns and opened up significant new markets in the structural domain. RPL can be made through many different ways but predominantly from HDPE. The stiffness of RPL can be increased by adding reinforcements, such as fiberglass bars.

The goal of the technical study is to design a reinforced RPL beam that can fulfill the same flexural strength requirements as a reinforced concrete beam or a wooden beam with the same span length. Reinforced concrete beams and wooden beams flexural test data and behaviors have been published in many studies; the following published cases were considered for the purpose of this study:

3.2.1. Wood Beam

Isopescu studied wood beam bending properties under static four-point bending test, they followed the ASTM-D143-09 (8) test standard in their experimental study. Nine 2600mm long rectangular wooden beams with cross-section dimensions of 100mm (b) x 160mm (h) were evaluated with a four-point bending test (Isopescu et al, 2012).
Figure 3-1. Four-point bending test setup, bottom span is 2400mm and top span is 800mm. (Isopescu et al, 2012)

Figure 3-2. Force vs displacement plot and failure modes (Isopescu et al, 2012).
Table 3-1. Four-point bend testing tabular data (Isopescu et al, 2012)

<table>
<thead>
<tr>
<th>Beam number</th>
<th>$t$ s</th>
<th>$\delta$ mm</th>
<th>$P$ N</th>
<th>$E_L$ MPa</th>
<th>$E_{L12}$ MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>286</td>
<td>24.31</td>
<td>27,430</td>
<td>8,109.96</td>
<td>8,525.51</td>
</tr>
<tr>
<td>2</td>
<td>261</td>
<td>23.55</td>
<td>22,890</td>
<td>6,986.07</td>
<td>7,407.20</td>
</tr>
<tr>
<td>3</td>
<td>306</td>
<td>23.20</td>
<td>28,950</td>
<td>8,968.88</td>
<td>9,509.55</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>20.64</td>
<td>30,810</td>
<td>10,729.01</td>
<td>11,311.11</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>20.69</td>
<td>30,700</td>
<td>10,664.87</td>
<td>11,275.63</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>23.05</td>
<td>30,000</td>
<td>9,354.66</td>
<td>10,031.37</td>
</tr>
<tr>
<td>7</td>
<td>301</td>
<td>24.50</td>
<td>30,530</td>
<td>8,956.50</td>
<td>9,658.40</td>
</tr>
<tr>
<td>8</td>
<td>301</td>
<td>24.35</td>
<td>27,500</td>
<td>8,117.30</td>
<td>8,680.03</td>
</tr>
<tr>
<td>9</td>
<td>321</td>
<td>32.06</td>
<td>30,600</td>
<td>6,860.18</td>
<td>7,356.44</td>
</tr>
<tr>
<td>Mean value</td>
<td>297.33</td>
<td>24.04</td>
<td>28,823</td>
<td>8,749.72</td>
<td>9,306.14</td>
</tr>
</tbody>
</table>

The following formulas were used to calculate the modulus of elasticity:

$$E_L = \frac{23PL^3}{108bh^3 \Delta} \quad E_{L12} = E_L \frac{1.857 - 0.0237W}{1.857 - 0.0237 \times 12}$$

3.2.2. Concrete Beam

Sangeetha et al studied reinforced concrete beam bending behavior under static four-point bending test. Ordinary Portland Cement (OPC) was used in the concrete mix. Two beams were tested after 28 days of concrete casting and two beams were tested after 56 days of concrete casting, all concrete beams had the same details as follows (Sangeetha et al 2014):

- Longitudinal reinforcement: Top reinforcement 2#10 & Bottom reinforcement 3#12
- Stirrups reinforcement: Diameter 8mm with 160mm spacing
- Length span of 2500mm with 250mm (h) X 150mm (b) cross-section
Figure 3-3. Four-point bend test setup (Sangeetha et al 2014).

Figure 3-4. Position of strain gauge and position of LVDT’s (Sangeetha et al 2014).
3.2.3. Reinforced Recycled Plastic Beam

Finite element analysis has been utilized to conduct virtual four-point bend test on various reinforced RPL beam designs. The ABAQUS solver has been used for this analysis. The reinforced RPL beam, the RPL (matrix) and the bars (reinforcement) were modeled using a full three dimensional finite element model with reduced-integration brick elements. To simulate the 4 point bending setup, proper boundary conditions were used to account for the contact between the roller supports and the RPL specimen.

Different beam cross sections and reinforcement volume fractions were investigated; the reinforced RPL beam designs were optimized to meet the same technical requirements of reinforced concrete beams and a wooden beams.
The simulation results shown in Figure 3-8 showed that reinforced RPL beam with 115mmX180mm (b x h) cross section and 15mm reinforcement diameter (4 bars) provided the same flexural strength as a 100mm x 160mm wooden beam.

Figure 3-7. FEM mesh model of the RPL 2600mmX115mmX180mm beam.
Figure 3-8. Four-bend simulation results of reinforced RPL 2600mmX115mmX180mm beam.

The simulation results presented in Figure 3-10 indicated that Reinforced RPL beam with 195mmX305mm (b x h) cross section and 35mm reinforcement diameter (4 bars) provided the same flexural strength as a 150mmX250mm (b x h) reinforced concrete beam.

Figure 3-9. FEM mesh model of the RPL 2500mm x 195mm x 305mm beam.
Figure 3-10. Four-bend simulation results of reinforced 2500mm x 195mm x 305mm beam.

In conclusion, the results in figure-10 and figure-8 show that an RPL beam can be designed to meet the flexural strength of a reinforced concrete beam or a wood beam with the same span length if it designed with a proper reinforcement and cross-section.

Virtual four-point bending test has been used the same way to determine the wooden beam cross-section that can meet the same flexural strength of concrete beams. The simulation results showed that a wood beam with a 170mm x 285mm (b x h) cross-section can meet the same flexural strength as a reinforced beam with a 150mm x 250mm cross-section.

The following table, Table 3-2 shows the cross-section designs of a reinforced concrete beam, a reinforced RPL beam and a wood beam with the same flexural strength.
Table 3-2. Four-point bend testing tabular data.

<table>
<thead>
<tr>
<th>Cross-sections with Comparable Structural Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reinforced Concrete Beam</strong></td>
</tr>
<tr>
<td>Cross-section</td>
</tr>
<tr>
<td>Reinforcement</td>
</tr>
</tbody>
</table>

3.3. **Sustainability Assessment:**

Sustainability is the ability to become and remain “Green” while balancing the impact on the “Triple Bottom Line” dimensions depicted in Figure 3-11:

- Environmental dimension
- Economic dimension
- Social dimension

![Figure 3-11. Triple Bottom Line dimensions.](image-url)
Sustainability assessment has been performed to assess the impact of the reinforced concrete beams, wooden beams and RPL beams on the three sustainability dimensions (triple bottom line).

3.3.1. Environmental Sustainability

In the environmental dimension of the sustainability assessment, the SimaPro LCA software package has been used to study the environmental impact of the structural beams. Three beam designs using three different structural materials have been evaluated: reinforced concrete, reinforced recycled plastic and wood.

3.3.2. Functional unit and system boundary

The functional unit is the amount of material that is needed to construct the structural beam. Table 3-3 presents the material quantities that are needed for the three different designs.

Table 3-3. Material quantities needed for the different designs.

<table>
<thead>
<tr>
<th>Reinforced Concrete Beam</th>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concrete</td>
<td>0.094 m³</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>218 lb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reinforced RPL beam</th>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RPL</td>
<td>0.149 m³</td>
</tr>
<tr>
<td></td>
<td>GFRP</td>
<td>0.01 m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wood Beams</th>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wood</td>
<td>0.121 m³</td>
</tr>
</tbody>
</table>
The scope of the LCA is cradle-to-construction phase; this includes all steps from raw material, acquisition/production, including transportation, all the way up to the completion of the beam construction. The demolition phase is excluded in this study.

3.3.3. Environmental impact assessment

A life cycle impact assessment is performed using SimaPro 8.0 LCA software package. Two methods have been chosen to conduct the assessment: Traci 2.1 v1.01 and Eco-invent. Assessment values were considered the same in both methods. Therefore, only results of the Traci 2.1 method were presented in this study.

Figure 3-12 demonstrates that the reinforced recycled plastic show the greatest environmental benefit for each of the 10 categories that have been evaluated. This was due to the largely reduced burden associated with extracting the reinforced recycled plastic material, the far less energy required to collect and re-use/recycled plastic. Moreover far less emission of Greenhouse gases (such: Carbon Dioxide (CO2), Methane (CH4), Nitrous Oxide (N2O) & Water Vapor (H2O)) were associated with the construction of the reinforced recycled plastic material. In addition, using recycled plastic lead to reduction of municipal solid wastes at landfill sites, which is one of the bigger factors for achieving a better ecosystem (Ecotoxicity).
Figure 3-12. Impact assessment of three structural materials on ten different environmental categories.

Environmental impact results (mainly with respect to ozone depletion, carcinogen and ecotoxicity) strongly suggest that using reinforced recycled plastic material for structural applications has a huge environmental advantage over the use of concrete and over the use of wood.

Sustainability assessment of each individual construction method has been performed independently in order to evaluate the relative impact of the constituents of each method.
Figure 3-13. Impact assessment of reinforced concrete beam on the ten different environmental categories.

Figure 3-13 shows that within the concrete beam construction the reinforcement (steel) has the highest negative impact on the environment. These results suggest that we need to optimize the amount of steel utilized in the concrete beam, and to try to come up with a design that requires less quantity of steel, if possible.

Figure 3-14. Impact assessment of recycled plastic beam on ten different environmental categories.
Figure 3-14 shows that within the recycled plastic beam construction, recycled plastic and GFRP reinforcement has almost the same impact on the environment. Therefore, it is worth evaluating different reinforcement types to lower the environmental impact.

![Figure 3-15. Impact assessment of wood beam on ten different environmental categories.](image)

As expected within the wooden beam construction the main contributor to the negative environmental impact is the cutting/manufacturing wood. The other factor in the process that might have a considerable effect is transportation, but in this case it was almost negligible since the wood supplier was within short distance.

Further investigation has been carried out to examine individual components impact on Ozone depletion and Global warming:
Figure 3-16. Impact of Reinforced Concrete Beam components on Ozone depletion.

Figure 3-17. Impact of Reinforced Concrete Beam components on Global warming

Figure 3-16 and Figure 3-17 show that the steel reinforcement has the highest impact on Ozone depletion and global warming
Figure 3-18. Impact of reinforced recycled plastic beam components on Ozone depletion.
Figure 3-19. Impact of reinforced recycled plastic beam components on Global warming.

Figure 3-18 and Figure 3-19 show that in the reinforced recycled beam construction, the Glass fiber has a higher impact on the Ozone depletion but the recycled plastic has a higher impact on the global warming.

LCA inventory list shows that glass fiber has higher emissions of Chlorofluorocarbons (CFCs) and Hydro-chlorofluorocarbons (HCFCs) gasses, which have higher impact on Ozone depletion while recycled plastic has higher emissions of Carbon Dioxide (CO2), Nitrogen Dioxide (NO2) and Methane (CH4) gases, which have higher impact on Global warming.
3.3.4. Economic Sustainability

The following are the material cost for each method:

Table 3-4. Material quantities needed for the different designs.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Material</th>
<th>Quantity</th>
<th>Price</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced Concrete</td>
<td>Concrete</td>
<td>4.9 m$^3$ = 171 ft$^3$</td>
<td>$75/ft^3$</td>
<td>$12,825</td>
</tr>
<tr>
<td></td>
<td>Reinforcing Steel</td>
<td>2412 lb</td>
<td>$0.2/lb</td>
<td>$483</td>
</tr>
<tr>
<td></td>
<td>Form Work - wood</td>
<td>0.15232 m$^2$ = 5.4 ft$^2$</td>
<td>$39/ft^2$</td>
<td>$210</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$13,518</strong></td>
</tr>
<tr>
<td>Reinforced RPL</td>
<td>RPL</td>
<td>4.17 m$^2$ = 146 ft$^2$</td>
<td>$0.72/lb</td>
<td>$8054</td>
</tr>
<tr>
<td></td>
<td>GFRP</td>
<td>365 lb</td>
<td>$1/ lb</td>
<td>$365</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$8,429</strong></td>
</tr>
<tr>
<td>Wood Beams</td>
<td>Wood</td>
<td>4.9 m$^2$ = 171 ft$^2$</td>
<td>$39/ft^3$</td>
<td><strong>$6,669</strong></td>
</tr>
</tbody>
</table>

The total sustainability cost of the reinforced recycled plastic beam is 60% lower than the total sustainability cost of the reinforced concrete beam. However, the total sustainability cost of the reinforced recycled plastic beam is 20% higher than that of its wooden counterpart. These values are the direct cost values for materials only. If we take
into consideration the cost of maintenance over the life time then the life-cycle cost of the concrete beams and wooden beams will be higher than that of recycled plastic beams.

3.3.5. Social Sustainability

Three methods were used to evaluate the social sustainability impact of the structural beams:

- Social Sustainability Evaluation Matrix (SSEM)
- Streamlined life cycle assessment (SLCA)

3.3.5.1. Social Sustainability Evaluation Matrix

SSEM is an Excel-based tool that was developed by Professor Krishna R. Reddy at UIC (Reddy et al 2014). It is used to assess social sustainability impact of four dimensions: Social-Individual, Socio-Institutional, Socio-Economic, and Socio-Environmental.

The scoring rate in this tool is configured as shown in Table 3-5.

<table>
<thead>
<tr>
<th>Score rating</th>
<th>Positive Impact</th>
<th>No Impact or Not Applicable</th>
<th>Negative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ideal</td>
<td>Improved</td>
<td>Diminished</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-2</td>
</tr>
</tbody>
</table>

The SSEM tool yielded the scoring results for the three constructions methods presented in Table 3-6.
Table 3-6. Scoring results.

### Social Sustainability Evaluation Matrix (SSEM)

<table>
<thead>
<tr>
<th>Social Sustainability Matrix</th>
<th>Concrete Beam</th>
<th>RPL Beam</th>
<th>Wood Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social</td>
<td>2</td>
<td>4</td>
<td>-4</td>
</tr>
<tr>
<td>Socio-Institutional</td>
<td>2</td>
<td>9</td>
<td>-5</td>
</tr>
<tr>
<td>Socio-Economic</td>
<td>1</td>
<td>5</td>
<td>-2</td>
</tr>
<tr>
<td>Socio-Environmental</td>
<td>-8</td>
<td>8</td>
<td>-7</td>
</tr>
<tr>
<td>Grand Score</td>
<td>-3</td>
<td>26</td>
<td>-18</td>
</tr>
</tbody>
</table>

Figure 3-21. SSEM results show that recycled plastic is at least twice better than concrete and wood.

3.3.5.2. Streamlined life cycle assessment (SLCA)

The SLCA method evaluates physical, chemical, shock, ergonomic, and noise hazards over the life span of the different designs. The scoring rate of this tool is configured as shown in...
The SLCA results of the construction methods of three types of beams are shown in Table 3-8, Table 3-9, and Table 3-10.

Table 3-8. SLCA results for the reinforced concrete beam.

<table>
<thead>
<tr>
<th></th>
<th>Physical Hazard</th>
<th>Chemical Hazard</th>
<th>Shock Hazard</th>
<th>Ergonomic Hazard</th>
<th>Noise Hazard</th>
<th>Row Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Manufacture</td>
<td>3.0</td>
<td>2.0</td>
<td>3.5</td>
<td>2.9</td>
<td>1.5</td>
<td>12.9</td>
</tr>
<tr>
<td>Product Delivery</td>
<td>2.9</td>
<td>4.0</td>
<td>4.0</td>
<td>2.5</td>
<td>2.5</td>
<td>15.9</td>
</tr>
<tr>
<td>Installation/Construction</td>
<td>2.0</td>
<td>3.8</td>
<td>4.0</td>
<td>1.5</td>
<td>2.1</td>
<td>13.4</td>
</tr>
<tr>
<td>Field Service</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>20.0</td>
</tr>
<tr>
<td>End Of Life</td>
<td>3.5</td>
<td>4.0</td>
<td>4.0</td>
<td>3.0</td>
<td>0.5</td>
<td>15.0</td>
</tr>
<tr>
<td>Column Score</td>
<td>17.9</td>
<td>21.8</td>
<td>23.3</td>
<td>16.4</td>
<td>12.1</td>
<td>78.2/100</td>
</tr>
</tbody>
</table>

Table 3-9. SLCA results for the RPL beam.
Table 3-10. SLCA results for the wood beam.

<table>
<thead>
<tr>
<th>RPL Beam: SLCA Health And Safety Matrix</th>
<th>Physical Hazard</th>
<th>Chemical Hazard</th>
<th>Shock Hazard</th>
<th>Ergonomic Hazard</th>
<th>Noise Hazard</th>
<th>Row Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery</td>
<td>3.0</td>
<td>2.0</td>
<td>3.5</td>
<td>2.5</td>
<td>1.5</td>
<td>13.3</td>
</tr>
<tr>
<td>Sorting and Reclaimer Operation</td>
<td>2.0</td>
<td>3.0</td>
<td>3.5</td>
<td>2.5</td>
<td>4.0</td>
<td>15.5</td>
</tr>
<tr>
<td>Product Delivery</td>
<td>1.5</td>
<td>2.0</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>14.2</td>
</tr>
<tr>
<td>Installation/Construction</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>3.5</td>
<td>3.0</td>
<td>18.4</td>
</tr>
<tr>
<td>Field Service</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>20.0</td>
</tr>
<tr>
<td>End Of Life</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>3.0</td>
<td>3.0</td>
<td>17.6</td>
</tr>
<tr>
<td>Column Score</td>
<td>18</td>
<td>19</td>
<td>23.3</td>
<td>19.6</td>
<td>19</td>
<td>98/120</td>
</tr>
</tbody>
</table>

The SLCA results show that the recycled plastic beam is 19.8% and 9.5% better than the concrete beam and the wood beam respectively.
3.4. **Summary and Conclusions**

The technical assessment presented in this study showed that the recycled plastic material can be designed for structural application and can substitute the reinforced concrete and wood materials in several structural applications.

Life cycle cost assessment showed that the reinforced recycled plastic material has great environmental benefit and that greenhouse gases emissions are much lower when using the recycled plastic material for construction compared to concrete and wood materials.

The recycled plastic beam cost was lower than the reinforced concrete beams but higher than wooden beams. Although it is higher than the cost of wooded beam, previous studies showed that maintenance requirements and cost over the life cycle of the recycled plastic beam is much lower than that of the concrete and wooden beams.

Using recycled plastic as a structural material has the highest score in all social dimensions. It reduces deforestation by substituting wood in many applications, reduces solid wastes at landfill, requires less maintenance, and retains new look for longer time.

3.5. **References**


- Keller T. Recent all-composite and hybrid fiber reinforced polymer bridges and buildings. Progress Struct Eng Mater, 2001


- Simulia, ABAQUS Documentation, version 6.14, 2014
• SimaPro 8.0 LCA package

• PlasticsEurope. Distribution of European plastic consumption according to its nature in millions of tons per year, Caudron, 2003; 2011.


4. FLEXURAL BEHAVIOR OF HDPE COMPOSITE BEAMS

4.1. Introduction

Recycled plastic lumber (RPL) is already identified as the best way of recycling high density polyethylene (HDPE) generated by post-consumer plastic containers collected in recycling programs across the country. RPL has been used by the construction industry in several non-load bearing applications, however there is a recent demand and efforts to migrate RPL into structural applications. Such applications include marine fenders, decking for residential and commercial uses, small span bridges, and other fresh and salt water shoreline applications. RPL has significant potential and advantages such as light weight, low cost and high resistance to environmental degradation. However it is fibrous material that has low stiffness compared to other structural materials. RPL material can be reinforced in order to increase its stiffness, as shown in Figure 4-1, so it can withstand structural loads. In this study we will use fiberglass as reinforcement.

Figure 4-1. RPL composite stress-strain curve.
The main problem of integrating RPL into structural applications is the lack of specifications and guidelines for analysis and design. Usually RPL is not homogeneous across its entire cross section, the inside core is a foam-like material and typically lighter than the outside perimeter which is a hard skin. Extracting RPL material property by using conventional dogbone tensile test is not sufficient to understand the overall behavior of structural elements. Studying the structural behavior of large sizes of actual structural elements such as RPL beams is important to develop specifications and guidelines for designing RPL structural elements.

The usability of RPL in the civil infrastructure applications is still at early stage due to a lack of design requirements and guidelines. The goal of this study is to contribute to the development of viable and safe structural design using RPL material. This experimental and numerical investigation focus on studying the flexural behavior of plastic lumber beams reinforced with Glass Fiber Reinforced Polymer (GFRP) reinforcing bars. The following parameters have been investigated in this study:

- Volume fraction of GFRP
- Cross-sectional area of the GFRP
- Cross sectional area of the beam
- Cross-sectional shape of the beam
- Span length of beam support
- Recycled plastic mix
4.2. **MATERIAL PROPERTIES**

4.2.1. **PRL mechanical property**

RPL material property has been characterized under tensile test using DIC optical technique. Dogbones dimensions were machined according to ASTM-D638 (Type-III). Four samples were prepared and tested. Figure 4-2 illustrates the sample dimensions.

![Figure 4-2. Dogbone coupon shape and dimension.](image)

Since we are using Digital Image Correlation (DIC) technique to extract the test data, we created a speckled pattern over the gauge area. This is achieved using two coat paints: black and white. First we coat the gauge region with black paint then spray white paint over it to create a random black-white speckled pattern over the gauge region as shown in Figure 4-3.
MTS load frame machine is used to pull the test specimens, the deformation of the specimen determined by means of Digital Image Correlation in conjunction with displacement and force readings from the load frame equipment. Table 4-1, Figure 4-4, and Figure 4-5 illustrate the results of the coupon testing.
Table 4-1. Tensile test results.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RPL</td>
<td>1</td>
<td>45.0</td>
<td>19.06</td>
<td>13.970</td>
<td>266.27</td>
<td>1298.5 MPA 188.3 ksi</td>
<td>13.17 Mpa 1.91 ksi</td>
<td>0.0349</td>
<td></td>
</tr>
<tr>
<td>RPL</td>
<td>2</td>
<td>45.0</td>
<td>19.04</td>
<td>13.950</td>
<td>265.61</td>
<td>1061.9 MPA 154 ksi</td>
<td>12.75 Mpa 1.85 ksi</td>
<td>0.0523</td>
<td></td>
</tr>
<tr>
<td>RPL</td>
<td>3</td>
<td>45.0</td>
<td>19.02</td>
<td>13.940</td>
<td>265.14</td>
<td>1362.6 MPA 197.6 ksi</td>
<td>12.65 Mpa 1.84 ksi</td>
<td>0.0210</td>
<td></td>
</tr>
<tr>
<td>RPL</td>
<td>4</td>
<td>45.0</td>
<td>19.03</td>
<td>13.940</td>
<td>265.28</td>
<td>1332 MPA 193.2 ksi</td>
<td>12.64 Mpa 1.83 ksi</td>
<td>0.0224</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1263.7 MPA 183.3 ksi</td>
<td>12.80 Mpa 1.86 ksi</td>
<td>0.0330</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4-4. Samples after testing, tested samples show brittle failure at the gage area.
4.3. **Experimental Study**

RPL beams were experimentally tested under three point bending test to determine the flexural modulus of elasticity ($E$), yield stress in bending, flexural stiffness ($EI$), and the mode of failure. In accordance with ASTM D6109 (2010), the specimen need to be loaded until rupture occurs in the outer fibers or until a maximum outer fiber strain of 3% is reached. During each test, load, deflection, and strain data were collected and recorded by using a data logger.

Two linear variable differential transducers (LVDTs) were placed at mid-span of the RPL specimen to measure deflection. The load was supplied at mid-span by means of a hydraulic loading system. The Load was applied at a rate of 0.25 in/min (6.35 mm/in.) until the ultimate load was reached.

![True Stress - Strain Response](image)

Figure 4-5. True Stress – True Strain for three test samples.
4.3.1. Beam Dimensions

The RPL had nominal rectangular dimensions of 10 in. x 10 in. (254 mm x 254 mm), 12 in. x 8 in. (304.8 mm x 203.2 mm), 8 in. x 12 in. (203.2 mm x 304.8 mm), and 12 in. x 12 in. (304.8 mm x 304.8 mm), manufactured as one continuous piece with no joints or splices. These RPL made from HDPE were combined with strengthening agents, UV-inhibitors, anti-oxidants, foam inducing chemicals resulting in a stable material that is better than traditional wood, and discontinuous fiber glass. Three batches with two different recycled plastic material properties were included in the experimental study:

4.3.1.1. First batch:

Total of three beams were tested, all of them had 10 in. x 10 in. (254 mm x 254 mm) square cross sections. Two beams were reinforced with 4 fiberglass rods; each rod had 1.375 in. (34.9 mm) diameter. One beam was reinforced with 4 fiberglass rods, each rod had 1.5 in. (38.1 mm) diameter. Since these beams failed due to rupture of recycle plastic material without utilizing the GFRP reinforcement effectively, other batches with different recycled plastic mix was used for further studies. The dimensions of batch-1 test specimens, the nominal shape, and reinforcing scheme are presented in Figure 4-6 and Table 4-2.

![Figure 4-6. Cross section of 10 in. x 10 in. beam with 4 GFRP bars.](image-url)
Table 4.2. Batch-1 test specimens dimensions.

<table>
<thead>
<tr>
<th>Specimen Designation</th>
<th>Width, in.</th>
<th>Depth, in.</th>
<th>$I_y$ (Moment of Inertia), in²</th>
<th>Weight per linear foot, lb/ft</th>
<th>Type E-Fiberglass Rods</th>
<th>Area of Fiberglass Rods, in²</th>
</tr>
</thead>
<tbody>
<tr>
<td>10x10-W758-FG4-1.375</td>
<td>10</td>
<td>10</td>
<td>777</td>
<td>38.9</td>
<td>4-1.375</td>
<td>5.96</td>
</tr>
<tr>
<td>10x10-W796-FG4-1.375</td>
<td>10</td>
<td>10</td>
<td>777</td>
<td>40.8</td>
<td>4-1.375</td>
<td>5.96</td>
</tr>
<tr>
<td>10x10-W718-FG4-1.5</td>
<td>10</td>
<td>10</td>
<td>777</td>
<td>36.8</td>
<td>4-1.50</td>
<td>7.08</td>
</tr>
</tbody>
</table>

Note: 1 in. = 25.4 mm, 1 lb/ft = 1.488 kg/m

4.3.1.2. Second batch:

Twelve specimens were tested, six specimens without reinforcement and six specimens with reinforcement. Different cross sections and different reinforcement diameter were used; the dimensions of the test specimens and the nominal shape and reinforcing scheme are presented in Figure 4-6 and Table 4-3.

Table 4-3. Batch-2 test specimens dimensions.

<table>
<thead>
<tr>
<th>Specimen Designation</th>
<th>Width, in.</th>
<th>Depth, in.</th>
<th>$I_y$ (Moment of Inertia), in²</th>
<th>Weight per linear foot, lb/ft</th>
<th>Type E-Fiberglass Rods</th>
<th>Area of Fiberglass Rods, in²</th>
</tr>
</thead>
<tbody>
<tr>
<td>10x10-W500-FG0</td>
<td>10</td>
<td>10</td>
<td>777</td>
<td>27.3</td>
<td>non</td>
<td>0</td>
</tr>
<tr>
<td>10x10-W516-FG0</td>
<td>10</td>
<td>10</td>
<td>777</td>
<td>28.2</td>
<td>non</td>
<td>0</td>
</tr>
<tr>
<td>10x10-W586-FG4-0.875</td>
<td>10</td>
<td>10</td>
<td>777</td>
<td>32</td>
<td>4-0.875</td>
<td>2.4</td>
</tr>
<tr>
<td>10x10-W570-FG4-0.875</td>
<td>10</td>
<td>10</td>
<td>777</td>
<td>31.1</td>
<td>4-0.875</td>
<td>2.4</td>
</tr>
<tr>
<td>10x10-W576-FG8-0.875</td>
<td>10</td>
<td>10</td>
<td>777</td>
<td>31.8</td>
<td>8-0.875</td>
<td>4.8</td>
</tr>
<tr>
<td>10x10-W608-FG12-0.875</td>
<td>10</td>
<td>10</td>
<td>777</td>
<td>33.8</td>
<td>12-0.875</td>
<td>7.2</td>
</tr>
<tr>
<td>10x10-W616-FG4-1.375</td>
<td>10</td>
<td>10</td>
<td>777</td>
<td>33.6</td>
<td>4-1.375</td>
<td>5.96</td>
</tr>
<tr>
<td>10x10-W646-FG4-1.375</td>
<td>10</td>
<td>10</td>
<td>777</td>
<td>35.2</td>
<td>4-1.375</td>
<td>5.96</td>
</tr>
<tr>
<td>8x12-W548-FG0</td>
<td>8</td>
<td>12</td>
<td>992</td>
<td>29.1</td>
<td>non</td>
<td>0</td>
</tr>
<tr>
<td>12x8-W540-FG0</td>
<td>12</td>
<td>8</td>
<td>447</td>
<td>28.7</td>
<td>non</td>
<td>0</td>
</tr>
<tr>
<td>8x12-W372-FG0-11ft</td>
<td>8</td>
<td>12</td>
<td>992</td>
<td>30</td>
<td>non</td>
<td>0</td>
</tr>
<tr>
<td>12x8-W372-FG0-11ft</td>
<td>12</td>
<td>8</td>
<td>447</td>
<td>30</td>
<td>non</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: 1 in. = 25.4 mm, 1 in² = 645.2 mm², 1 lb/ft = 1.488 kg/m
4.3.1.3. Third batch:

Six specimens were tested with reinforcement. Each beam had 12 in. x 12 in. (304.8 mm x 304.8 mm) square cross sections with 4 fiberglass rods, all rods diameter were 1.25 in. The dimensions of the test specimens and the nominal shape and reinforcing scheme are presented in Figure 4-6 and Table 4-4.

Table 4-4. Batch-3 test specimens dimensions.

<table>
<thead>
<tr>
<th>Specimen Designation</th>
<th>Width, in.</th>
<th>Depth, in.</th>
<th>( I_g ) (Moment of Inertia), in(^2)</th>
<th>Wt per linear foot, lb/ft</th>
<th>Type E-Fiberglass Rods</th>
<th>Area of Fiberglass Rods, in(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12x12-W750-FG4-1.25</td>
<td>12</td>
<td>12</td>
<td>1605</td>
<td>62.5</td>
<td>4-1.25</td>
<td>5.4</td>
</tr>
<tr>
<td>12x12-W736-FG4-1.25</td>
<td>12</td>
<td>12</td>
<td>1605</td>
<td>61.3</td>
<td>4-1.25</td>
<td>5.4</td>
</tr>
<tr>
<td>12x12-W752-FG4-1.25</td>
<td>12</td>
<td>12</td>
<td>1605</td>
<td>62.7</td>
<td>4-1.25</td>
<td>5.4</td>
</tr>
<tr>
<td>12x12-W758-FG4-1.25</td>
<td>12</td>
<td>12</td>
<td>1605</td>
<td>63.2</td>
<td>4-1.25</td>
<td>5.4</td>
</tr>
<tr>
<td>12x12-W742-FG4-1.25</td>
<td>12</td>
<td>12</td>
<td>1605</td>
<td>61.8</td>
<td>4-1.25</td>
<td>5.4</td>
</tr>
<tr>
<td>12x12-W756-FG4-1.25</td>
<td>12</td>
<td>12</td>
<td>1605</td>
<td>63.0</td>
<td>4-1.25</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Note: 1 in. = 25.4 mm, 1 in\(^2\) = 645.2 mm\(^2\), 1 lb/ft = 1.488 kg/m

The fiberglass rods were placed symmetrically in the corners of the cross section in accordance with ASTM D4476 (2009). The test specimens were received in good condition and stored on a flat surface prior to testing. All test specimens were pre-test conditioned for 40 hours in ambient environment of the lab at 73\(^{°}\)F (22.8\(^{°}\) C) and a relative humidity (RH) of about 50%.

The specimen designation is as follows: the first two numbers are the cross-sectional dimensions (width by height) in inches. The “W” represents the weight of the beam and is followed by the numerical weight of the beam in pounds. The "FG" stands for fiber glass reinforcement polymer bars and the number following the FG is the number of bars. The last number is the diameter of one of these bars. The beams tested for 11 ft span were followed by ‘*’ symbol at the end.
4.3.2. **Test Setup**

A special self-sustained rigid testing frame equipped with a hydraulic machine and a load cell was used for all tests. The specimens were tested using a three point bending test with the load applied at the center of a simply supported span. The three point bending test set up is shown in Figure 4-7. According to ASTM D6109 (2010), the distance between the supports is required to be 16 times the depth of the beam (tolerance +4 and -2) with an overhang distance beyond the support equal to minimum 10% of the span length. The beam clear span length was set to 14 ft (4.27 m). In order to minimize excessive indentations at the nose and support locations the radius of the nose and supports was fabricated to 3 in. (76.2 mm).

![Figure 4-7. Test Setup.](image)

**4.4. Analytical Investigation**

The modulus of elasticity and yield stress were determined from these full-scale sized test specimens. The yield stress was evaluated at a yield load $P$ or at load $P$ for 1%
strain, whichever is less. In the event where a specimen did not fail nor did it show a true yield point after reaching an outer fiber strain up to 3%, the yield stress was evaluated using the load P at 1% strain.

For these full scale size test specimens the strain ($\varepsilon$) was calculated from the experimental measured deflections by adopting the Florida department of transportation standards (2010) for calculating the structural plastic properties. The strain, yield stress, stiffness and modulus of elasticity were calculated using the equations (1), (2), (3) and (4) respectively.

$$\text{Strain, } \varepsilon = \frac{6 \times h \times \delta}{L^2} \tag{1}$$

Where,

$$h = \text{Depth of the section (in or mm)}$$

$$\delta = \text{Deflection (in or mm)}$$

$$L = \text{Span length (in or mm)}$$

$$\text{Yield stress, } F_y = \frac{(P \times L)}{(4 \times S)} \tag{2}$$

Where,

$$P = \text{Load as stated above (kips or MPa)}$$

$$S = \text{Section modulus of gross section (in}^3\text{ or mm}^3)$$

$$\text{Stiffness, } EI = \frac{(P' \times L^3)}{(48 \times \Delta)} \tag{3}$$

Where,

$$P' = \text{Load that is } \frac{1}{2} P \text{ at yield (kips or Mpa)}$$
\( L \) = Span length (in or mm)

\( \Delta \) = Deflection at the location of load corresponding \( P' \) (in or mm)

\( E \) = Modulus of elasticity

\[
\text{Modulus of Elasticity, } E \quad = \frac{EI}{I_g} \quad (4)
\]

Where,

\( EI \) = calculated from load deflection curve from equation (3)

\( I_g \) = gross moment of inertia (in\(^4\) or mm\(^4\))

4.5. **Discussion of Experimental Results**

4.5.1. **First Batch**

All of the specimens failed in rupture of the recycled plastic material as shown in Figure 4-8. These results show that these failures were mostly dependent on the recycled plastic material properties rather than GFRP reinforcement properties. In this first batch, the recycled plastic failed before the GFRP reinforcement because the beam was over-reinforced. This failure can be considered as a safe failure. In this case it is considered safe because the beam did not fail catastrophically since the GFRP bars remained intact.

Table 4-5 presents the calculated test results for the first batch while Figure 4-9 and Figure 4-10 show the load-displacement and stress-strain curves for the first batch of beams. It includes two identical beams of 4-1.375” [i.e. 4 bars of 1.375 in (34.9 mm) diameter] GFRP and 4-1.5” GFRP reinforced beams. One of the 4-1.375” GFRP reinforced beams unexpectedly failed in a lower load possibly due to recycled plastic material defects. In
addition, the 4-1.5” beam showed lower stiffness than the 4-1.375” beam and failed unexpectedly with the same ultimate load of 4-1.375.”

The strains in the GFRP bars were around 1.7% at the failure of these beam specimens. However, since GFRP rupture strain is around 2.5-3.0%, there is a possibility to achieve higher ultimate load capacity if the recycle plastic material has less rigidity. Therefore, recycled plastic mix proportions were changed by adjusting the additives (fiber volume fraction etc.) in the second batch in order to improve the effect of reinforcement on load capacity. The first batch will not be further discussed due to material composition, rod location and failure mode not being optimal.

Figure 4-8. Typical failure for first batch of beams.

Table 4-5. Calculated test results for the first batch.

<table>
<thead>
<tr>
<th>Specimen Designation</th>
<th>EI (Stiffness) x 10^8, lb-in²</th>
<th>Load at Yield, kips</th>
<th>Ultimate Load, kips</th>
<th>Yield Stress in Bending, psi</th>
<th>Ultimate Stress at Failure, psi</th>
<th>Ultimate Deflection, in</th>
<th>Ultimate Strain at Failure, με</th>
</tr>
</thead>
<tbody>
<tr>
<td>10x10-W758-FG4-1.375</td>
<td>7.69</td>
<td>30.2</td>
<td>41.8</td>
<td>8150</td>
<td>11290</td>
<td>7.8</td>
<td>16500</td>
</tr>
<tr>
<td>10x10-W796-FG4-1.375</td>
<td>6.22</td>
<td>26.4</td>
<td>32.4</td>
<td>7150</td>
<td>8740</td>
<td>6.3</td>
<td>13400</td>
</tr>
<tr>
<td>10x10-W718-FG4-1.5</td>
<td>6.63</td>
<td>28.5</td>
<td>41.7</td>
<td>7700</td>
<td>11263</td>
<td>8.0</td>
<td>17100</td>
</tr>
</tbody>
</table>
Figure 4-9. Load deflection curves for first batch of beams.

Figure 4-10. Stress-strain curves for first batch of beams.
4.5.2. **Second Batch**

4.5.2.1. Effect of area of GFRP bars

Figure 4-11 and Figure 4-12 show the load deflection and stress strain curves for the 14 ft (4.27 m) span beams tested with different GFRP reinforcement areas. All beams have the same cross section dimensions and the same span length. Inspection of Figure 4-11 and Figure 4-12 indicates that as the reinforcement area increases the stiffness and the load capacity increase except for beams 10x10-W576-FG8-0.875 and 10x10-W608-FG12-0.875. Plastic beam 10x10-W576-FG8-0.875 shows lower load capacity than plastic beam 10x10-W570-FG4-0.875, but higher stiffness. The reason for these variations is that the top cover to the top reinforcement of the beam was not adequate. During testing of the beams the plastic material was damaged and the loading cylinder reached the fiber glass rods and damaged them. Failure of the beams without GFRP bars were very brittle resulting in sudden failure of the beams into two pieces. Addition of GFRP reinforcement increased the load capacity of beams by about five times and the stiffness by about three times compared to beams without GFRP reinforcement. Also, using GFRP reinforcement deflection can be reduced more than 40%.
Figure 4-11. Load-deflection behavior for 10 in x 10 in plastic beams.

Figure 4-12. Stress-strain behavior for 10 in x 10 in plastic beams.
Plastic beam 10x10-W646-FG4-1.375 with a GFRP area of 5.96 in\(^2\) (3845 mm\(^2\)) experienced higher load capacity than plastic beam 10x10-W608-FG12-0.875 with an area of 7.2 in\(^2\) (4645 mm\(^2\)). The reason for this unexpected result was inadequate plastic cover which was explained earlier (see Figure 4-13(a)). The stiffness was almost the same for beams 10x10-W646-FG4-1.375 and 10x10-W608-FG12-0.875 because with the latter beam one of the top bars slipped as shown in Figure 4-13(b).

Figure 4-13. (a) Cross section of beam 10x10-W608-FG12-0.875 (b) Slip in GFRP bar.

Figure 4-14 shows the stiffness of the beams versus the area of fiber glass rods. Inspection of Figure 4-14 reveals that the stiffness increases linearly as the area of GFRP reinforcement increases. It is difficult to use many small bars instead of larger bars in the manufacturing process because GFRP rods tend to sag under to high temperature. Therefore, it is difficult to maintain the required locations of the GFRP rods throughout the beam length.
Figure 4-14. Stiffness verses area of GFRP bars.

Table 4-6 presents the calculated test results for the second batch:

Table 4-6. Calculated test results for the second batch.

<table>
<thead>
<tr>
<th>Specimen designation</th>
<th>El (Stiffness) 1 x 10^8, lb-in^2</th>
<th>Yield stress in bending, psi</th>
<th>Stress at 3% strain, psi</th>
<th>Ultimate stress at Failure, psi</th>
<th>Ultimate deflection, in</th>
<th>Ultimate strain at failure, με</th>
</tr>
</thead>
<tbody>
<tr>
<td>10x10-W500-FG0</td>
<td>1.91</td>
<td>1683</td>
<td>2517</td>
<td>2564</td>
<td>17.9</td>
<td>37943</td>
</tr>
<tr>
<td>10x10-W516-FG0</td>
<td>1.88</td>
<td>1761</td>
<td>2673</td>
<td>2831</td>
<td>17.5</td>
<td>37096</td>
</tr>
<tr>
<td>10x10-W586-FG4-0.875</td>
<td>3.33</td>
<td>4024</td>
<td>8529</td>
<td>8777</td>
<td>14.9</td>
<td>31373</td>
</tr>
<tr>
<td>10x10-W570-FG4-0.875</td>
<td>3.86</td>
<td>4020</td>
<td>8292</td>
<td>8810</td>
<td>16.4</td>
<td>34955</td>
</tr>
<tr>
<td>10x10-W576-FG8-0.875</td>
<td>5.42</td>
<td>6184</td>
<td>N/A</td>
<td>8069</td>
<td>6.5</td>
<td>13923</td>
</tr>
<tr>
<td>10x10-W608-FG12-0.875</td>
<td>5.97</td>
<td>7019</td>
<td>N/A</td>
<td>9941</td>
<td>7.3</td>
<td>15450</td>
</tr>
<tr>
<td>10x10-W616-FG4-1.375</td>
<td>5.86</td>
<td>6940</td>
<td>N/A</td>
<td>10702</td>
<td>10.1</td>
<td>21400</td>
</tr>
<tr>
<td>10x10-W646-FG4-1.375</td>
<td>6.08</td>
<td>6915</td>
<td>N/A</td>
<td>13604</td>
<td>11.8</td>
<td>25100</td>
</tr>
<tr>
<td>8x12-W548-FG0</td>
<td>1.78</td>
<td>946</td>
<td>N/A</td>
<td>1315</td>
<td>9.4</td>
<td>24087</td>
</tr>
<tr>
<td>12x8-W540-FG0</td>
<td>0.98</td>
<td>1011</td>
<td>N/A</td>
<td>1356</td>
<td>12.6</td>
<td>21504</td>
</tr>
<tr>
<td>8x12-W372-FG0</td>
<td>1.64</td>
<td>987</td>
<td>N/A</td>
<td>1335</td>
<td>5.5</td>
<td>22588</td>
</tr>
<tr>
<td>12x8-W372-FG0</td>
<td>1.09</td>
<td>1151</td>
<td>N/A</td>
<td>1495</td>
<td>8.2</td>
<td>22616</td>
</tr>
</tbody>
</table>

Note: 1 lb-in^2 = 292.9 kg-mm^2, 1 ksi = 6.89 MPa, 1 kips = 4.448 kN, 1 psi = 6.89 kPa, 1 in = 25.4 mm
4.5.2.2. Effect of strong versus weak axis on unreinforced beams

Load-deflection and stress-strain curves for different cross sections are shown in Figure 4-15 and Figure 4-16. Load-deflection and stress-strain curves for plastic beam 8x12-W548-FG0 experienced more deflection, higher load capacity, and higher stiffness than plastic beam 12x8-W540-FG0. As expected from the observed behavior, strong axis plastic beams yield higher load carrying capacities and higher stiffness while having less deflections. However, both of them failed with almost the same stress while having slight strain differences since failure depends on the recycle plastic material properties. The failure stresses were 1315 psi (9.07 MPa) and 1356 psi (9.35 MPa) for beams 8x12-W548-FG0 and 12x8-W540-FG0 respectively. At failure, deflections were 9.4 and 12.6 inches and the strains were 24087 and 21504 με for beams 8x12-W548-FG0 and 12x8-W540-FG0, respectively, as shown in Table 4-6.

![Figure 4-15. Load-deflection of different cross sectional beams.](image-url)
4.5.2.3. Effect of different span lengths on unreinforced beams

The load-deflection and the stress-strain curves for unreinforced beams of 8”x12”, 12”x8” with two different span lengths of 14 ft (4.27 m) and 11 ft (3.35 m) are shown in Figure 4-17 and Figure 4-18. All beams failed at an ultimate stress of around 1350 psi, except plastic beam 12x8-W372-FG0' failed at an ultimate stress of 1500 psi as shown in Figure 4-18. The ultimate load, load at yield and yield stress increased when the span length decreased, as shown in Table 4-6. The percentage difference of load capacity for strong axis to weak axis decreased as span length decreased. All of these beams failed in a very brittle manner as shown in Figure 4-19 since they were not reinforced with GFRP.
Figure 4-17. Load deflection curves for different span length.

Figure 4-18. Stress-strain behavior for different span length for unreinforced beams.
Figure 4-19. Failure of 8 in x 12 in beams tested for (a) weak axis (b) strong axis capacity.

4.5.2.4. Effect of changing recycled plastic material

Figure 4-20 shows the load deflection behavior of 10x10-W758-FG4-1.375 and 10x10-W646-FG4-1.375 beams. It is clear from the Figure 4-20 that first batch had more stiffness than the second batch but had less ductility and load capacity. However, this stiffness increment is negligible when compared to the stiffness increment due to GFRP reinforcement area increases.

Figure 4-20. Load-deflection behavior of two batches.
4.5.3. **Third Batch**

Figure 4-21 shows the load deflection curves for six tested beam using 12 ft (3.66 m) span, each beam had 4 GFRP reinforcing bars. All beams have the same cross section dimensions, and the same reinforcement area. Inspection of Figure 4-21 indicates that as the reinforcement area increases the stiffness and the load capacity increase. Results were consistent across all the tested samples; this is an indication that the plastic mix property was very well controlled and consistent across all the samples.

![Load deflection curves third batch beams](image)

Figure 4-21. Load deflection curves third batch beams.
Table 6. Calculated test results for the third batch

<table>
<thead>
<tr>
<th>Specimen designation</th>
<th>El (Stiffness) $1 \times 10^8$, lb-in$^2$</th>
<th>Maximum yield stress in bending, psi</th>
<th>Strain at maximum yield stress, $\mu\varepsilon$</th>
<th>Ultimate strain at failure, $\mu\varepsilon$</th>
<th>Stress at 1% strain, psi</th>
<th>Ultimate deflection at failure in</th>
</tr>
</thead>
<tbody>
<tr>
<td>12x12-W749-FG4-1.25</td>
<td>5.46</td>
<td>7183</td>
<td>27627</td>
<td>43500</td>
<td>3422</td>
<td>12.839</td>
</tr>
<tr>
<td>12x12-W735-FG4-1.25</td>
<td>5.98</td>
<td>7586</td>
<td>27702</td>
<td>34716</td>
<td>3734</td>
<td>10.085</td>
</tr>
<tr>
<td>12x12-W751-FG4-1.25</td>
<td>5.06</td>
<td>8460</td>
<td>33998</td>
<td>35468</td>
<td>3330</td>
<td>10.448</td>
</tr>
<tr>
<td>12x12-W757-FG4-1.25</td>
<td>5.36</td>
<td>8856</td>
<td>34678</td>
<td>37221</td>
<td>3540</td>
<td>10.94</td>
</tr>
<tr>
<td>12x12-W741-FG4-1.25</td>
<td>5.38</td>
<td>8890</td>
<td>34915</td>
<td>35584</td>
<td>3577</td>
<td>10.483</td>
</tr>
<tr>
<td>12x12-W742-FG4-1.25</td>
<td>5.25</td>
<td>8905</td>
<td>34948</td>
<td>35615</td>
<td>3494</td>
<td>10.509</td>
</tr>
</tbody>
</table>

Note: 1 lb-in$^2 = 292.9$ kg-mm$^2$, 1 ksi = 6.89 MPa, 1 kips = 4.448 kN, 1 psi = 6.89 kPa, 1 in = 25.4 mm
4.6. **Finite Element analysis**

Finite element analysis has been utilized to further investigate and optimize the structural behavior of RPL composite beams. A full three-dimensional finite element model for the RPL composite beam structure and the supports of the three-point bend fixture were modeled and simulated. The modeling software HyperMesh was used to build the mesh model, and ABAQUS solver was used to conduct the simulation.

The Plastic mesh (matrix) and GFRP rods mesh (fiber) were modeled with reduced-integration brick elements C3D8R. [C= Continuum stress/displacement, 3D=three-dimensional, 8= number of nodes, R= reduced integration]

![Figure 4-22. 8-node brick element with one integration point in the middle of the element.](image)

![Figure 4-23. Brick element with one integration point in the middle of the element.](image)
The supports of the 3 points bending setup were simulated using rigid rollers in ABAQUS. Contact interactions were applied accordingly between the supports and specimen to mimic the actual friction. Coulomb friction model is used in Abaqus, it relates the max allowable shear stress to the contact pressure between the contacting surfaces. These surfaces can take shear stresses up to certain value before they start sliding on each other. Critical shear stress, \( \tau_{cr} \), between two contacted surfaces with pressure \( p \), defined as \( \tau_{cr} = \mu p \). This equation determines when the transition point from sticking to slipping state occurs. \( \mu \) in this equation refers to coefficient of friction. This friction model assumes that \( \mu \) is isotropic friction (same in all directions). The shear components along the contacting surfaces are \( \tau_1 \) and \( \tau_2 \). Equivalent shear stress for these two orthogonal components is

\[
\tau = \sqrt{\tau_1^2 + \tau_2^2}.
\]

Coefficient of friction at initiation of slipping is different from coefficient of friction at during slipping. The coefficient at initiation of slipping called static friction coefficient, where coefficient during slipping called kinetic friction coefficient. The model assumes that the friction decrease exponentially from the static coefficient to the kinetic coefficient as shown in this equation:

\[
\mu = \mu_k + (\mu_s - \mu_k) e^{-d_c \dot{\gamma}_{eq}}
\]

Where,

- \( \mu_k \): Kinetic friction coefficient,
- \( \mu_s \): Static friction coefficient.
- \( d_c \): decay coefficient,
- \( \dot{\gamma}_{eq} \): slip rate
coefficient of friction ($\mu$) of value 0.1 showed good correlation between experimental and simulation, hence $\mu = 0.1$ was used in the study.

The bottom support was restrained in all degrees of freedoms to avoid rigid body motion. The top support only allowed to move vertically. The following are the boundary condition definitions for the rollers:

- **TOP-FIXTURE, 1, 2, 0.0**  
  [U1 and U2 are fixed]
- **TOP-FIXTURE, 3, 3, 15**  
  [U3 assigned to move by 15mm]
- **TOP-FIXTURE, 4, 6, 0.0**  
  [U4, U5 and U6 are fixed]
- **BOTTOM-FIXTURE-REF, 1, 6, 0.0**  
  [All degree of freedom are fixed]

Figure 4-24 presents the labeling conventions that are used in ABAQUS for degrees of freedom:

![Degree of freedom labeling conventions in ABAQUS.](image)

Figure 4-24. Degree of freedom labeling conventions in ABAQUS.
Figure 4-25. Matrix (RPL) and fiber (GFRP) mesh models.

Figure 4-25 shows a plots of matrix (RPL) and fiber (GFRP) mesh models. Matrix mesh model consisted 100456 brick elements (C3D8R) and 86521 nodes, fiber mesh model consisted 14400 brick elements (C3D8R) and 19282 nodes. Figure 4-26 shows simulation model of RPL composite beam under three point bend.

Figure 4-26. Simulation model of RPL composite beam under three point bend.
4.6.1. **Finite Element Results**

The first step in FEM study is to build simulation model that capable to mimic the actual test. Once a good representative simulation model is established, it can be used to investigate the sensitivity of the predicted force-deflection and stress-strain results to the following parameters:

- Rebar Volume Fraction
- Span Length
- Beam Shape

4.6.2. **Representative Models**

Convergence study is needed to build a good and reliable representative model; the following parameters have been considered during to build the model:

- Material models,
- Mesh refinement
- P-refinement

These parameters have been optimized until the convergent solution converged to the exact solution within 5%, which is the difference between the FEM convergent solution $\hat{S}$ and the exact solution $\hat{S}$ as shown in the convergent solution schematic in Figure 4-27.
Virtual three point bend test have been conducted utilizing simulation for the following configurations:

- 8’x12’ RPL beams without reinforcement:
- 8’x12’ RPL beams without reinforcement:
- 10’x10’ RPL beams with 4 rebar reinforcement, 1.375” rebar diameter
- 10’x10’ RPL beams with 4 rebar reinforcement, 0.875” rebar diameter
- 12’x12’ RPL beams with 4 rebar reinforcement, 1.25” rebar diameter

Figure 4-28 shows a comparison between testing and simulation results for the RPL beams without reinforcement. Simulation results “force-deflection” correlates very well with testing results.
Figure 4-28. Comparison between simulation and testing for RPL beams without reinforcement.

Figure 4-29 shows a comparison between testing and simulation results for the RPL beams with reinforcement. Simulation results “force-deflection” correlates very well with testing results.

Figure 4-29. Comparison between simulation and testing for RPL beams with reinforcement.
4.6.3. **Effect of Rebar Volume Fraction**

The more reinforcement added into the metal matrix, the stiffer the composite beams get. With increasing reinforcement content, the interactions between reinforcement and matrix increases. This increases the capability of the reinforcement to transfer stress from the matrix to themselves, and increases the work hardening of the matrix. The effect of the fiber volume fraction was investigated by using different volume fractions 2%, 4.5%, 8%, and 12.5% while keeping the cross section and span fixed as shown in Figure 4-30.

![Rebar Volume Fraction Diagrams](image)

**Figure 4-30.** RPL beam cross section with different rebar volume fraction.
Figure 4-31. Force deflection of RPL beams using different rebar volume fractions.

Figure 4-31 shows that increasing the reinforcement volume fraction increases the elastic modulus and the work-hardening rate of the composite beams as expected. If certain beam stiffness is required for specific industrial application, the RPL composite beam could be designed with a proper reinforcement volume fraction to meet a specific requirement.

4.6.4. Effect of Span Length

Four unreinforced 12”x8” beams with four different span lengths: 10 ft, 12 ft, 14 ft and 16 ft have been simulated under three point bend loading. Load-deflection curve results shown in Figure 4-32 reveals that ultimate load, load at yield, yield stress and work-hardening rate increased as the span length decreased.
4.6.5. Effect of Beam Shape

As noted in the experimental study, the RPL material is not homogeneous across the beam cross-section, the inside core is a foam-like material and typically lighter than the outside because the temperature during manufacturing is higher inside the beam and it takes longer time too cool down. Hollow beam have been proposed to achieve better and faster cooling process inside the beam, and it will lead to lighter weight and less RPL material consumption.

Nine reinforced beams with five different cross-sectional shapes have been analyzed under three-point bend loading using 12ft span. All the beams had 12”x12” cross-sectional dimensions with 4 reinforcing bars, each rebar had a diameter of 1.25”. Figure 4-33 Shows the schematic of the different beams cross-sectional shapes.

Figure 4-32. Force deflection of RPL beam under different span lengths.
Figure 4-33. Different beams cross-section.
The load-deflection curves are plotted in Figure 4-35, results show that all of the proposed cross-sectional shapes capture at least 88% of from the full beam stiffness. The best cross-sectional shape is the one with circular hollow; it captures 97% of the full beam stiffness. It shows that the beam cross-sectional shape could be optimized to reveal better thermal processing and lower weight without impacting the beam stiffness.

Figure 4-36 shows force-deflection results of different cross-sectional shapes however the matrix cross-sectional area is the same which means that the reinforcement volume fraction is the same. Cross-sectional-Ib configuration showed the lowest stiffness where cross-sectional-Ob showed the best stiffness among the proposed designs.
Figure 4-35. Force deflection of RPL beam using different cross sections but same volume fraction.

Figure 4-36 shows the force-deflection results of the different cross-sectional shapes and different matrix cross-sectional (volume fraction is different). Cross-sectional-I2 configuration showed the lowest stiffness where cross-sectional-O1 showed the best stiffness among the proposed designs. Cross-sectional-O1 captures ~95% of the full beam stiffness.
4.7. Summary and Conclusions

Recycled plastic lumbers (RPLs) beams were studied experimentally and computationally to investigate the structural behavior and mechanical properties of RPL beams. The parameters tested were the cross-sectional area of the GFRP reinforcement, strong versus weak axis of the RPL, span length, and recycled plastic mix. The following conclusions and recommendations can be made based on the findings:

- Addition of GFRP reinforcement bars is more effective than addition of additives to the recycle plastic material to increase the ultimate load capacity and the stiffness of the Plastic beams.

- The stiffness of the recycled plastic beams increased linearly with the increase of area of GFRP rods.

Figure 4-36. Force deflection of RPL beam using different cross sections and different volume fraction.
- The ultimate load capacity can be increased about 5 times and the stiffness can be increased about 3 times while decreasing the deflection about 40% by increasing the GFRP reinforcement area.

- It is very advantageous to increase the load capacity and the stiffness by increasing the reinforcement area after finalizing and/or selecting the best suitable recycle plastic mix. Using a stiffer recycle plastic mix may not allow the GFRP to be fully stressed as recycle plastic may fail before fully utilizing the GFRP reinforcement.

- Virtual testing can be achieved through simulation, where we can optimize the design strength with much less time and cost.

- Elastoplastic analysis using finite element models can be used for accurate prediction of the tensile stress-strain behavior of composites.

- Different beam shapes (I-beam & hollow beam) can be used instead of full beam with comparable stiffness results (90%-95%) and with much better manufacturing advantages (lower weight, less material, faster cooling …etc)
4.8. References


5. STRUCTURAL ADHESIVE BULK BEHAVIOR

(The content of this chapter was published, as Shibli A, Issa M. Structural Adhesive Behavior – Experimental and Computational Study. Conference on Reliable Engineering Computing on May 26th 2014).

5.1. Introduction

Structural adhesive has been around for a long time. They have been made from plants and animals up until the 19th century; however in the 20th century synthetic chemicals have taken over. Adhesives have been used in all types of manufacturing: clothing, shoes, aerospace, automobile, and even human tissues. Adhesive bonding is used as a mean to join different parts together; it has been increasingly used in constructions of aircraft and automobile as a replacement of traditional joining methods such bolting, riveting and spot-welding.

Adhesive bonding is still in its infancy in civil infrastructure applications due to the lack of design guidelines and consistent specifications. Although it has been studied and widely used in the fields of aerospace and automotive, these studies cannot be directly transferred to the civil infrastructure domain. Adhesive bonding for civil structural application have essential differences with respect to type of materials, loadings, geometries and environmental conditions.

The traditional bolted joint methods in civil infrastructure applications have gone a long way in creating appropriate technologies and gained years of design experience, which cannot be easily replaced. Switching from traditional joining methods to adhesives bonding in civil infrastructure applications requires a large investment to establish a level of understanding comparable to that associated with traditional joining methods. In particular,
it is crucial to characterize and fully understand bonded joint behavior, strength and failure properties, and to be able to predict them for a given geometries and loads.

The attractiveness of adhesives stems from their unique combinations of properties which include:

- High strength
- light weight
- Dimensional stability
- Ease of use
- Uniform loading without stress concentrations
- high resistance to environmental degradation
- Rapid installation

Utilizing adhesive bonding in civil infrastructure applications does not only replace the traditional joining methods of bolting and riveting, but also open the door for using new structural materials such reinforced polymers (FRP) composites, recycled plastic materials and other new composites. These newly proposed structural materials are brittle and cannot be joined using traditional joining methods, which create stress concentrations and lead to premature failure. Furthermore, holes in the bolted joints are areas for stress concentrations and moisture ingress, which can impact the overall structure durability. Adhesive joints are excellent candidate to replace traditional joining methods in these scenarios. They lead to uniform loading without stress concentrations and without moisture ingress.

**5.2. Literature Review**

- Basic Properties of Adhesives
A definition of an adhesive is a material which can be applied between two surfaces of materials to join them together and prevent separation. An adhesive must wet to the substrate surface in order to make proper contact, and then it must harden to a cohesively strong solid in order to resist separation.

There are basic terms that should be known when dealing with adhesives such shelf-life and pot-life:

- Shelf-life: is the time that adhesive can be stored before use
- Pot-life: is the maximum allowed time between adhesive mixing and application

Basic Chemistry of Adhesives

Adhesives are polymers which can have linear, branched or cross-linked chains as shown in Figure 5-1:

![Linear, Branched, Cross-linked Structures](image)

**Figure 5-1.** Linear, branched and cross-linked structures of polymers.

Linear and branched polymers have similar properties; they flow at high temperatures and dissolve with the use of solvents. Cross-linked polymers do not flow at high temperatures and do not dissolve. Structural adhesives are cross-linked polymers.
Various adhesives contain additives that are not polymers to enhance the adhesive’s properties. The following are some of the widely used types of additives and the role they play:

- Stabilizer additive to resist degradation,
- Plasticizer additive to lower the glass transition temperature and increase flexibility
- Powder mineral fillers to reduce shrinkage

Polymerization

Polymerization is the joining of individual monomers to form a polymer. Monomers can combine straight, branched or cross-linked polymer as shown in Figure 5-1. These different polymer structures have different mechanical properties.

- Thermoplastics: Polymers with straight and branched chains are thermoplastics. They soften and liquefy under heat, and solidify under cooling.
- Thermoset materials: Polymers with cross-linked chains are thermosets. They do not melt under heat since their chain segments are strong bonded, chemically. The chemical bond is demonstrated in black dot in Figure 5-2.
The mechanical behavior of thermoplastics and thermoset materials are different. The schematic in Figure 5-3 shows polymers behavior at increasing temperature.
Glass Transition Temperature

Understanding the behavior of polymer under the influence of temperature is important as it indicate different mechanical behaviors and stiffness values of the polymer. Below glass temperature the polymer have high stiffness values. These values decrease when the glass temperature is exceeded because of the increasing mobility of the molecules at higher temperatures.

5.3. Material and Test Methods

Structural adhesive “Loctite” will be used in this study to bond two different substrate materials: Al-6061 and Polycarbonate. Adhesive and substrate materials have been characterized under different loading modes and loading rates:

- Loading modes – tensile loading and shear loading
- Loading rates – quasi-static rate and dynamic rate

5.3.1. Substrates test methods

Substrates (Al-6061 and Polycarbonate) mechanical properties have been characterized under tensile test using DIC optical technique. The dimensions of the “Dogbone” specimens are shown in Figure 5-4, five samples were prepared and tested for each material.
Since we are using Digital Image Correlation (DIC) technique to extract the test data, we created a speckled pattern over the gauge area for each sample as shown in 5-5.

Figure 5-5. Substrate dogbone coupon with speckled pattern.
MTS load frame machine is used to pull the test specimens, the deformation of the specimen determined by means of Digital Image Correlation in conjunction with displacement and force readings from the load frame equipment.

5.3.2. Adhesive test methods

Among different standard authorities including ASTM (American Society for Testing and Materials) and ISO (International Organization of Standardization), a variety of test methods have been developed and established to characterize the mechanical properties of adhesives. The following are some of the tests that are needed to characterize the bulk behavior of cured adhesives:

- Stress-strain analysis
- Glass transition temperature
- Coefficient of thermal expansion

It is crucial to understand adhesive’s mechanical behavior under different loading modes and different loading rates. The set of tests that are needed could be determined by the type of application that the adhesive will be used for, such strain level, strain rate, load, etc…

Loading mode:

- Tensile loading (Dogbone and butt joint tests)
- Shear stress (Lapshear test)
- Cleavage (Wedge test)
- Peel (180° peel test)
Loading rate:

- Quasi-static test
- Dynamic test
- Cyclic loading
- Long-term static loading
- Dynamic Mechanical Testing

Table 5-1 lists the test modes and methods that will be discussed in this study:

<table>
<thead>
<tr>
<th>Test Type</th>
<th>ASTM Standards</th>
<th>Standards' Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Test</td>
<td>ASTM D638</td>
<td>Extracting tensile properties using dogbone</td>
</tr>
<tr>
<td></td>
<td>ASTM-D2094</td>
<td>Guide and test preparation</td>
</tr>
<tr>
<td></td>
<td>ASTM-D2095</td>
<td>Extracting tensile properties using butt-joint</td>
</tr>
<tr>
<td>Shear Test</td>
<td>ASTM-D4896</td>
<td>Guide and test preparation</td>
</tr>
<tr>
<td></td>
<td>ASTM-D5656</td>
<td>Extracting shear strength properties</td>
</tr>
<tr>
<td></td>
<td>ASTM-D3983</td>
<td>Extracting shear Modulus</td>
</tr>
<tr>
<td>Tensile Test</td>
<td>Ball Drop at different Heights</td>
<td>Extracting Kinetic Energy</td>
</tr>
</tbody>
</table>

Adhesive’s mechanical properties have been characterized under tensile and shear load modes, at low and high loading rates test using DIC optical technique. Figure 5-6 shows tensile coupon dimensions.
Lap-shear test has been conducted using Al substrates, **Figure-7** show shear coupon dimensions for an individual substrate.

Each lap-shear coupon sample include two Al substrates with structural adhesive between them as shown in Figure 5-8. Adhesive dimension is 0.5mm x 5mm x 25mm. Lap-shear samples were cured for at least 14 days to reach full strength per supplier recommendation.
5.4. Mechanical Properties

The following are mechanical properties for the substrate materials and adhesive.

5.4.1. Substrate Mechanical Properties

Stress-strain curve for Al-6061 under tensile testing is shown in Figure 5-9, mechanical property values are listed in Table 5-2.

Figure 5-9. True stress-strain curve of Al-6061 material.
Table 5-2: Mechanical property of Al-6061 material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus [GPa]</th>
<th>Yield Stress [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-6061</td>
<td>67</td>
<td>271</td>
<td>11</td>
</tr>
</tbody>
</table>

Stress-strain curve of Polycarbonate material under tensile testing is shown in Figure 5-10, mechanical property values are listed in Table 5-3.

![Stress-strain curve of Polycarbonate material under quasi-static and dynamic rates.](image)

Figure 5-10. Stress-strain curve of Polycarbonate material under quasi-static and dynamic rates.

Table 5-3: Mechanical property of Polycarbonate material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Loading Rate</th>
<th>Modulus [GPa]</th>
<th>Yield Stress [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polycarbonate</td>
<td>Quasi-static</td>
<td>2.9</td>
<td>49</td>
<td>249</td>
</tr>
<tr>
<td></td>
<td>Dynamic 80/s</td>
<td>2.9</td>
<td>88</td>
<td>39</td>
</tr>
</tbody>
</table>

5.4.2. Adhesive Mechanical Properties

Adhesive has been characterized under tensile and shear loading at quasi-static and high loading rates.
5.4.2.1. Tensile Test Results

Stress-strain curve of the “Loctite” adhesive under tensile testing at low and high rates are shown in Figure 5-11 and the mechanical properties are listed in Table 5-4.

![Stress-strain curve of adhesive material under tensile loading.](image)

**Figure 5-11. Stress-strain curve of adhesive material under tensile loading.**

<table>
<thead>
<tr>
<th>Loading Rate</th>
<th>Modulus [MPa]</th>
<th>Yield Stress [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-static</td>
<td>125</td>
<td>5.1</td>
<td>9</td>
</tr>
<tr>
<td>Dynamic 100/s</td>
<td>326</td>
<td>10.9</td>
<td>3.4</td>
</tr>
</tbody>
</table>

5.4.2.2. Shear Test Results

Stress-strain curve of the “Loctite” adhesive under shear testing at low and high rates are shown in Figure 5-12 and the mechanical properties values are listed in Table 5-5.
Figure 5-12. Stress-strain curve of adhesive material under shear loading.

Table 5-5. Mechanical property of adhesive material under shear loading.

<table>
<thead>
<tr>
<th>Loading Rate</th>
<th>Modulus [MPa]</th>
<th>Ultimate Shear Stress [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-static</td>
<td>42</td>
<td>10.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Dynamic 2000/s</td>
<td>55</td>
<td>31</td>
<td>1.2</td>
</tr>
</tbody>
</table>

5.5. Material and Test Methods

5.5.1. Adhesive Material Model

Adhesive test results showing that adhesive is plastically deforming during testing, so plasticity should be accounted for in the material model. Also, test results show that adhesive behavior is sensitive to the loading rate in both ranges: elastic range and plastic range. Based on these findings the following material models will be considered in the study:

- Linear Elastic
- Linear Elastic-Plastic
ABAQUS FEA solver will be used in this study; material model will be created in the ABAQUS format.

5.5.1.1. Linear Elastic Model

Elastic response fully specified by Young’s modulus, E, and Poisson’s ratio, v. Test results showed that elastic response is sensitive to the loading rate. Young’s modulus at low rate is 125MPa where Young’s modulus at high rate is 326MPa. Since in the elastic material model we can use only one Young’s modulus value, we used an averaged modulus value in the elastic range.

ABAQUS elastic material model:

```
*MATERIAL, NAME=LOCTITE-ELASTIC
*DENSITY
  0.0012
*ELASTIC, TYPE=ISO
  225, 0.44
```

5.5.1.2. Linear Elastic-Plastic Model

First step in creating elastic-plastic material model is to convert the nominal stress-strain to true (Cauchy) stress-strain using the following relations:

\[
\sigma_{true} = \sigma_{nom}(1 + \varepsilon_{nom}) \\
\varepsilon_{true} = \ln(1 + \varepsilon_{nom})
\]

The elastic-plastic model assumed isotropic yield and hardening behavior. Plastic data was used in terms of true stress and true plastic strain. True plastic strain obtained from the total true strain as shown in the following equations:
ABAQUS elastic-plastic material model for the adhesive following the aforementioned

\[ \varepsilon_{\text{true}}^p = \varepsilon'_{\text{true}} - \varepsilon^e_{\text{true}} \]

\[ \varepsilon_{\text{in}}^p = \ln(1 + \varepsilon_{\text{nom}}) - \frac{\sigma_{\text{true}}}{E} \]

5.5.2. Substrate Material Model

The test results of the substrates show that both materials (Aluminum and Polycarbonate) are plastically deforming during tensile testing as expected, both materials are not sensitive to the loading rate in the elastic region. Elastic-plastic material models have been created for both materials.

5.6. Material Model Validation

There are several studies on structural adhesives; most of these studies follow the assumption that structural adhesives behave elastically linear. One of the important steps towards greater use of structural adhesives in civil structural applications is to characterize and understand their behavior accurately. The following experimental and computational study aimed to investigate the structural adhesive behavior and its impact at a system level.

Adhesive coupon test results revealed that adhesives behavior is sensitive to the loading rate and mode, not only in the plastic region but also in the elastic region. Different material models (elastic and elastic-plastic) were considered for the adhesive in order to find out the best representative material model that can mimic its behavior.
5.6.1. **Experimental Study**

Sandwich structures were constructed where the adhesive was sandwiched between two different plates; Al-6061 plate at the top and polycarbonate plate at the bottom. Two different configurations were considered, equal-length-plate sandwich structure and unequal-length-plate sandwich structure. Figure 5-13 shows adhesive and plate dimensions for each configuration.

Figure 5-14 shows actual sandwich structures with mounted strain gauges at the center of the top plate and at the center of the bottom plate. These Sandwich structures were tested under quasi-static and dynamic loadings.

**Configuration-1: Equal length adherends**

![Configuration 1 Diagram]

**Configuration-2: Unequal length adherends**

![Configuration 2 Diagram]

Figure 5-13. Equal-length-plate and unequal-length-plate sandwich structure configurations.
5.6.1.1. Quasi-static bending test

The planar bend test (four-point bend) has been extensively used to determine the strength of brittle materials. Similar technique was used in this study to bend the sandwiched plates in order to induce stress and strain state to the structure. The roller supports were positioned 35mm and 60mm apart respectively. Two strain gauges were mounted on the sandwiched plates, one at the center of the top plate and one at the center of the bottom plate.
a) Equal-length-plate sandwich structure (Figure 5-15)

Figure 5-15. Equal-length-plate sandwich structure under quasi-static loading.

Figure 5-16 and Figure 5-17 present the Force-Displacement and Force-Strain test results for the equal-length-plate sandwich structure.

Figure 5-16. Force-displacement results for the equal-length-plate sandwich structure.
b) Unequal-length-plate sandwich structure (Figure 5-15)

Figure 5-17. Force-strain results for the equal-length-plate sandwich structure.

Figure 5-18. Unequal-length-plate sandwich structure under quasi-static loading.

Figure 5-19 and Figure 5-20 present the Force-Displacement and Force-Strain test results for the unequal-length-plate sandwich structure.
Figure 5-19. Force-displacement results for the unequal-length-plate sandwich structure.

Figure 5-20. Force-strain results for the unequal-length-plate sandwich structure.
5.6.1.2. Dynamic bending test

The test fixture used to generate dynamic planar loading of the sandwich. The vehicle was positioned in the center of four point bending setup. A steel ball was dropped on the specimen to generate the dynamic loadings. Acceleration was monitored and used as boundary conditions in the dynamic bend simulations. Figure 5-21 to Figure 5-23 illustrate the test setup as well as the results obtained.

Figure 5-21. Unequal-length-plate sandwich structure under dynamic loading test.
Figure 5-22. Acceleration test measurement of top roller during the 35cm ball drop test.

Figure 5-23. Strain test measurement of the top and bottom strain gauges during the dynamic test.
5.6.2. **Computational Study**

A full three-dimensional finite element model of the sandwiched structure (Al plate, Adhesive and PC plate), and the supports of the four-point bend fixture were built using the modeling software ABAQUS. The Plates and the adhesive were modeled with reduced-integration brick elements. The two strain gauges were modeled as two membrane elements [0.8 x 0.8mm]. Boundary conditions were applied accordingly similar to previous models. Figure 5-24 presents the ABAQUS model.

![Figure 5-24. Plot of the simulation mesh model.](image)

5.6.2.1. **Quasi-Static Bending Simulation**

Two sandwich structure configurations were investigated in the quasi-static simulation as we showed earlier in Figure 5-13. Elastic-plastic material models were used for the substrates (Al and PC), where two different material models (elastic and elastic-plastic) were explored for the adhesive. Displacement loading was applied at a reference node of the top roller fixture. Force, displacement and strain (at the top plate center and at the bottom plate center) results were reported and correlated with experimental results to verify the best material modeling approach. Figure 5-25 and Figure 5-26 presents the results:
Figure 5-25. Force-displacement testing and simulation results of the unequal-length-plate sandwich structure.

Figure 5-26. Force-displacement testing and simulation results of the unequal-length-plate sandwich structure.
5.6.2.2. Dynamic Bending Simulation

The unequal-length-plate sandwich structure was investigated in the dynamic simulation. Elastic-plastic material models were used for the substrates (Al and PC), where three different material models (elastic and elastic-plastic) were explored for the adhesive.

Similar to the method employed by Tee (Tee et al 2004) was used in this study; the acceleration of the top roller fixture was extracted during the dynamic test which was then used as input initial loading condition in the simulation model. This method eliminates the complexity of the simulation model between the dropped ball and the fixture while maintaining accurate predictions. Top and bottom strain results were reported and correlated with experimental results to verify the best material model that can mimic the adhesive behavior under dynamic loading. Figure 5-27 presents the results:

Figure 5-27. Strain results of the top and bottom strain gauges during dynamic testing and simulation.
5.7. **Discussion**

- Quasi-Static bend simulations of the equal-length-plate sandwich structure showed good correlation between experimental and simulation results, for all adhesive material models used in the simulations. Results showed that force-displacement response was not affected by the adhesive stiffness which was expected as the adhesive layer will not affect the overall sandwich structure since it is thinner and less stiff than the adherend substrates. However, for force-strain response, the results are more interesting because they were not affected by the adhesive material modeling approach. This was attributed to the fact that the bottom rollers forcing the PC plate had the same curvature as the Al plate. The equal-length-plate configuration did not seem to serve as a good validation tool.

- Quasi-Static bend simulations of the unequal-length-plate sandwich structure showed that the overall behavior of the structure was sensitive to the adhesive material modeling approach. Force-displacement results and force-strain results showed that the linear-elastic material model will over predict the stiffness of the sandwich structure where the elastic-plastic material model mimics the experimental results much better. As the elastic material model did not account for plasticity, the adhesive did not soften up in simulations; and therefore, the PC plate will follow the Al plate curvature. The force-displacement results and the force-strain results show that simulation correlates well with experiments when elastic-plastic material model is used.
Dynamic bend simulations with unequal-length-plate sandwich structure showed that the overall behavior of the structure was sensitive to the adhesive material modeling approach. Strain-time simulation results at the center of top Al plate did not exhibit any dependence on the adhesive modeling approach; this was expected as the force is applied directly on the Al plate. However, strain-time simulation results at the bottom PC plate were sensitive to the adhesive material modeling approach. The elastic-plastic material modeling approach predicted the testing results very well, unlike the elastic and material modeling approach which correlated poorly with experimental results because they did not account for plasticity.

5.8. **Summary and Conclusion**

A numerical and experimental study that investigated the behavior of a structural adhesive under quasi-static and dynamic loading was presented. Through the presented results which are specific to the sandwich structure materials used in this study, the following conclusions can be drawn:

- The sandwich structure with unequal-length plates is able to capture the sensitivity to the adhesive material modeling approaches. However, the sandwich structure with equal-length plates is insensitive to the adhesive layer and failed as a configuration for capturing or investigating adhesive behavior and properties.

- Comparison between numerical and experimental results from both the quasi-static and dynamic simulation results show that the elastic-plastic material model mimics the adhesive material behavior better than the elastic and elastic-viscoelastic material
models, due to the ability of the elastic-plastic model to account for adhesive plasticity.

- Although both of the elastic and plastic phases of this specific adhesive are loading rate dependent, plastic behavior of the adhesive has bigger impact than its elastic behavior on the overall sandwich structure behavior. This is due to the fact that the adhesive will start deforming while the adhered substrates are still in their elastic regions.

5.9. References


6. STRUCTURAL ADHESIVE JOINT BEHAVIOR

6.1. Introduction

Adhesive joints are being increasingly used in structural applications due to their unique characteristics and advantages. Recently, many structural industries have considered utilizing adhesives for joining load-bearing components. Adhesives can be excellent candidates for replacing traditional joining methods such as bolting and riveting, especially for scenarios involving Fiber Reinforced Polymers (FRP) composites. The attractiveness of adhesives stems from their unique combination of properties, which include: high strength, light-weight, dimensional stability, high resistance to environmental degradation and ease of use. The traditional bolted joint methods have gone a long way in creating appropriate technologies and have gained years of design experience, which cannot be easily replaced. Accordingly, switching from traditional joining methods to adhesives bonding in civil infrastructure applications requires a large investment to establish a level of understanding comparable to that associated with traditional joining methods. In particular, it is crucial to characterize and fully understand bonded joint behavior, strength and failure properties, and to be able to make predictions for given geometries and loads.

The objectives of this study are:

i) Investigate the bulk behavior of structural adhesives and HDPE material

ii) Investigate the failure limits and failure modes of structural adhesives on the coupon level

iii) Develop a material model that is able to simulate the adhesive failure limits which is needed for computational studies.
6.2. Materials and Test Methods

Four materials have been used as the substrate material, three HDPE materials and one Polycarbonate material. Table 6-1 lists the substrate materials and the source of these materials.

Table 6-1. List of substrate materials and their source.

<table>
<thead>
<tr>
<th>Material</th>
<th>HDPE-Grey</th>
<th>HDPE-Tangent-Red</th>
<th>HDPE-McMaster-White</th>
<th>Polycarbonate (PC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier</td>
<td>Tangent</td>
<td>Tangent</td>
<td>McMaster</td>
<td>McMaster</td>
</tr>
</tbody>
</table>

Two structural adhesives have been considered for this study. Table 6-2 lists the structural adhesives and their source of these materials.

Table 6-2. List of structural adhesives and their source

<table>
<thead>
<tr>
<th>Structural Adhesive</th>
<th>DP 8010</th>
<th>Loctite-3035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier</td>
<td>3M</td>
<td>Henkel</td>
</tr>
</tbody>
</table>

These adhesives are two part acrylic based adhesives with a mixing ratio of 10:1, methacrylate base resin with an amine accelerator. The technical data sheets published by suppliers indicated that these structural adhesives are possible candidates for bonding low surface energy materials such as HDPE. Table 6-3 summarizes technical data that have been published by suppliers for these two adhesive materials:
Table 6-3. Adhesives’ mechanical properties by suppliers.

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Chemical Type</th>
<th>Curing Time @ 22C</th>
<th>Time to handling strength @ 22C</th>
<th>Work Life @ 22C</th>
<th>Shear Strength using HDPE substrates @ 22C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loctite-3035</td>
<td>Two-part Acrylic adhesive</td>
<td>8-24 hrs</td>
<td>1.5-2 hrs</td>
<td>10-12 min</td>
<td>13.7 MPa</td>
</tr>
<tr>
<td>3M-DP 8010</td>
<td>Two-part Acrylic adhesive</td>
<td>8-24 hrs</td>
<td>1.5-2 hrs</td>
<td>10-12 min</td>
<td>6 MPa</td>
</tr>
</tbody>
</table>

6.2.1. Substrates test methods

Substrate materials have been characterized under tensile testing. The Digital Image Correlation (DIC) optical technique has been used to extract stress-strain curves and understand their behavior. In addition, cyclic testing has been performed to evaluate the true yield point.

Dog-bone specimen dimensions are shown in Figure 6-1. Five samples have been prepared and tested for each material.

![Figure 6-1. Dogbone dimensions, units in mm.](image)

Since we are using the Digital Image Correlation (DIC) technique to extract the test data, we created a speckled pattern over the gauge area for each of the tested samples as shown in Figure 6-2.
Figure 6-2. Substrate dogbone coupon with speckled pattern.

The MTS load frame machine was used to pull the test specimens, the deformation of the specimen was determined by means of Digital Image Correlation in conjunction with displacement and force readings from the load frame equipment. Figure 6-3 shows the test setup using the DIC technique.

Figure 6-3. Tensile test setup using DIC technique.
6.2.2. Adhesive bulk test methods

Dog-bone samples have been machined out of structural adhesive sheets and used for tensile testing following the ASTM D638 test method.

Preparing Dog-bone Coupon for adhesive tensile testing

Since these structural adhesives exist in a liquid condition (uncured), we had to mold them in sheet shapes and cure them first. The two part fixture shown in Figure 6-4 has been designed and used to mold 180mm x 180mm x 2mm sheets of adhesive. The material has been cured for 24 hours based on supplier recommendation.

![Figure 6-4. Molds for adhesives.](image)

Figure 6-5 shows the bottom part dimensions including the cavity. The top part has the same design and dimensions, however without cavity.
ISO-15166 standard has been followed to prepare adhesive bulk material. Thin polytetrafluorene (PTFE) release sheets were used to guarantee easy release of the cured adhesive sheet from the clamping fixture as shown in Figure 6-6.

Laser cutting was used to cut dog-bone coupons out of the cured adhesive sheet. Figure 6-7 shows an adhesive dog-bone with the speckled DIC pattern.
6.3. Extracted Mechanical Properties

The following are the mechanical properties of the substrate (HDPE) material and the adhesive that were extracted from testing.

6.3.1. Substrate mechanical property

The stress-strain curve for the HDPE-Tangent-Gray under tensile testing is shown in Figure 6-8 with the extracted mechanical property values listed in Table 6-4.

![True Stress-Strain Response](image)

Figure 6-8. True stress-strain curve of HDPE-Tangent-Gray material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus [MPa]</th>
<th>Yield Stress [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE-Tangent-Gray</td>
<td>775</td>
<td>7.64</td>
<td>5.6</td>
</tr>
</tbody>
</table>
Figure 6-9 shows the HDPE sample after tensile testing. Tested samples show brittle failure at the gage area. Figure 6-10 shows the DIC strain contour plot during tensile testing with an average strain at the marked area before failure of 5.6%. DIC successfully captured the failure location and shape as well as the strain deformation level at failure.

Figure 6-9. HDPE-Tangent-Gray sample after testing, tested samples show brittle failure at the gage area.

Figure 6-10. DIC strain contour plot.
6.3.2. Adhesive mechanical property

3M-DP-8010 adhesive has been characterized under tensile loading. Figure 6-11 shows the stress-strain curve with the extracted mechanical property values listed in Table 6-5.

![True Stress-Strain Response](image)

Figure 6-11. True stress-strain curve of 3M-DP-8010.

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus [MPa]</th>
<th>Yield Stress [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE-Tangent-Gray</td>
<td>432</td>
<td>6.15</td>
<td>75</td>
</tr>
</tbody>
</table>

Table 6-5. Mechanical property of 3M-DP-8010 material.

Figure 6-12 shows adhesive dog-bone before and after testing. It is obvious that the tested samples plastically deformed.
6.3.3. Material Models

HDPE-Tangent-Gray and 3M-DP-8010 tensile test results show that both materials were plastically deforming during tensile testing. Elastic-plastic material models have been created for both materials. The elastic-plastic model assumed isotropic yield and hardening behavior. Plastic data was used in terms of true stress and true plastic strain. True plastic strain obtained from the total true strain as shown in the following equations:

\[ \varepsilon_{\text{true}}^p = \varepsilon_{\text{true}}^t - \varepsilon_{\text{true}}^e \]

\[ \varepsilon_{\ln}^p = \ln(1 + \varepsilon_{\text{nom}}) - \frac{\sigma_{\text{true}}}{E} \]

Elastic-plastic material models for the HDPE-Tangent-Gray and 3M-DP-8010 following the aforementioned equations.
6.4. Experimental Study

The aim of this experimental study is to evaluate the bond strength of different structural adhesives, and to find a good candidate to be used for bonding HDPE substrates. The impact of the following parameters will be investigated:

- Substrate
- Adhesive
- Thickness
- Loading rate
- Loading mode

The aforementioned factors were studied at different loading modes; tensile and shear modes. These loading modes are the dominant modes in structural applications. The American Society for Testing and Materials (ASTM) methods has been followed to characterize bond behavior of the structural adhesive. Table 6-6 shows a list of ASTM tests and specifications that have been followed in this study.

Table 6-6. List of ASTM standards for adhesive testing under tensile and shear loads

<table>
<thead>
<tr>
<th>Test Type</th>
<th>ASTM Standards</th>
<th>Standards' Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Test - Butt-Joint Test</td>
<td>ASTM-D2094</td>
<td>Guide and test preparation</td>
</tr>
<tr>
<td></td>
<td>ASTM-D2095</td>
<td>Extracting tensile properties using butt-joint</td>
</tr>
<tr>
<td>Shear Test - Lap-Shear Test</td>
<td>ASTM-D4896</td>
<td>Guide and test preparation</td>
</tr>
<tr>
<td></td>
<td>ASTM-D5656</td>
<td>Extracting shear strength properties</td>
</tr>
<tr>
<td></td>
<td>ASTM-D3983</td>
<td>Extracting shear Modulus</td>
</tr>
</tbody>
</table>
6.4.1. Tensile testing - Butt Joint

ASTM D2095 was used for butt-joint tensile testing. Figure 6-13 presents a schematic that has been shared in the ASTM D2095 test specification:

Figure 6-13. Test specimens and attachment fixtures based from ASTM D2095.

The same test procedure as shown in Figure 6-13 has been followed in this study, however with slight modification.

Figure 6-14. Butt-Joint test specimens and attachment fixtures used in current study.
Figure 6-14 shows the test specimens and test fixtures used in this study. It follows ASTM-D2095 specifications; however the bottom base has been modified with a long slot to allow testing with higher loading speeds by providing more distance to account for longer travel during transient velocity.

Four different substrates are tested under butt-joint tensile testing using the two different structural adhesives: 3M-DP-8010 and Loctite-3035. Each substrate had different tensile specimen dimensions; this is because the original plates that we machined the specimens from had different dimensions. This should not affect the results in our study. Figure 6-15 shows Butt-Joint test specimen dimensions for the four substrate materials.

![Figure 6-15. HDPE Test specimens’ dimensions for butt-joint tensile testing.](image)

6.4.2. Preparing butt-joint test specimens:

3M-DP-8010 and Loctite-3535 adhesives are both developed for low surface energy plastics, so there was no need for any specific surface treatment processing. To ensure better bonding strength, the surface was cleaned using 91% alcohol to remove any debris and contaminations. Figure 6-16 shows the processes of building tensile specimens for one of the HDPE substrates, steps are as follow:
- Sandpaper and clean the surface
- Add rectangular shim to control area and thickness of adhesive
- Dispense adhesive in the rectangular shim
- Combine every two samples in a way that the pin holes are vertical to each other
- Clamp the specimens and put in the oven for 1hr at 80C

Figure 6-16. Processes of building test specimens for butt-joint tensile testing.

The same process was followed to prepare all the butt-joint test specimens for all substrates. Once the specimens were prepared and clamped, they were cured for 48hrs.
6.4.3. **Lap Sear Test:**

ASTM-D3165-07 “Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies” has been followed during shear testing. The same butt-joint fixture has been used in this test. Figure 6-17 shows the schematic that has been shared in the ASTM test specification:

![Figure 6-17. Test specimens and attachment fixtures based from ASTM D3983.](image)

The length of overlap has been estimated according to the following relationship, which was specified in this test method:

\[
L = \frac{Ft_y T}{\tau}
\]

Where:
- \(L\) = length of overlap, mm
- \(T\) = thickness of metal, mm
- \(Ft_y\) = yield point of metal (or the stress at proportional limit), MPa
- \(\tau\) = 150% of the estimated average shear strength in the adhesive bond, MPa

The values of these parameters in this test are:

- Thickness of HDPE = 12mm minimum
- Yield stress of HDPE = 7.5 MPa
- Estimated shear strength of the adhesive = 4 MPa
- \(L = \frac{(7.5*12)}{(1.5*4)} = 15\) mm maximum
The process of preparing shear specimens is similar to the butt joint specimens. In addition, a gluing jig was designed to control the initial wet glue-line thickness as illustrated in Figure 6-20.
The same ASTM-D3165 test procedure has been followed in this study, the same test fixture was used for tensile and shear testing. Figure 6-21 shows a lap-shear test specimen inside the test fixture.

![Diagram of lap shear test specimen and attachment fixtures](image)

Figure 6-21. Lap Shear test specimens and attachment fixtures used in current study.

**6.5. Discussion of Experimental Results**

The impacts of the following parameters have been investigated in this study:

- Substrate: three different types of HDPE (HDPE-Grey, HDPE-Tangent-Red and HDPE-McMaster-White) and one type of Polycarbonate (PC).
- Adhesive: two structural adhesives were investigated: 3M-DP-8010 & Loctite-3535.
- Thickness: two different adhesive thicknesses were investigated, 0.5mm and 1mm.
- Loading Mode: Tensile and shear loadings
o Loading Rate: 0.1mm/s and 1mm/sec

o Failure Mode

6.5.1. Effect of substrate

Four substrates were explored in this study: HDPE-Grey, HDPE-Tangent-Red, HDPE-McMaster-White and PC. All the test specimens were prepared, cured and tested the same way. Figure 6-22 shows built up samples of different HDPE materials for butt-joint testing.

![Figure 6-22. Built up samples of different HDPE materials for butt-joint testing.](image)

The first patch of HDPE-Tangent-Red specimens failed at the pin location as shown in Figure 6-23. This failure is an indication that the strength of the bonded area of 400mm² is stronger than the peak load of 1420N as shown in Figure 6-24. All the specimens failed at approximately 1420N which means that strength of samples were consistent in their strength.
Figure 6-23. HDPE-Tangent-Red tested samples.

Figure 6-24. Force vs Displacement for HDPE-Tangent-Red butt-joint test using 400mm² bond area.

Based on these results, the bonded area was reduced from 400mm² down to 225mm² by using a rectangular shim between the two bonded pieces to control the area and the thickness.
Results of the butt-joint test using the different substrates are shown in Figure 6-25 and Figure 6-26. The results show that HDPE-McMaster-White has the lowest strength bond.
and that HDPE-Grey and HDPE-Tangent-Red have a much higher strength bond. The main reason for this variation is that HDPE-Tangent-Red and HDPE-Grey have a skin layer which increases the bonding strength. PC has the highest bond strength as expected.

6.5.2. Effect of adhesive

Two structural adhesives were investigated, 3M-DP-8010 and Loctite-3035. The test specimens were prepared and cured the same way. Figure 6-27 shows the force-displacement curve for butt-joint tensile test.

![Force vs Displacement using different structural adhesive.](image)

Results in Figure 6-28 show that the bond strength between the 3M-DP-8010 adhesive and the HDPE substrate is 36% higher than the bond strength between the Loctite-3535 adhesive and the HDPE substrate. Based on these results the 3M-DP-8010 will be used for the rest of the study.
6.5.3. **Effect of thickness**

The impact of thickness has been evaluated under tensile and shear loadings.

Figure 6-29. Force vs Displacement using different adhesive thickness.

Lap shear test results show that the bond strength of the thicker adhesive is 13% higher than the thinner adhesive, as shown in Figure 6-29 and Figure 6-30. This result might be due to the fact that, in this case, the thicker adhesive wets the surface better than the
thinner adhesive. Furthermore, elongation using the thicker adhesive is 35% more than the elongation of the thinner adhesive because the thicker adhesive is able to stretch more before de-bonding. The results also show that the specimen stiffness during loading is the same. Therefore, the thickness does not impact the overall stiffness of the specimen.

Butt-joint test results show that increasing the thickness increases the bond strength. The bond strength of HDPE-Tangent-Gray with 1mm adhesive is approximately 30% higher than the bond strength of HDPE-Tangent-Gray with 0.5mm adhesive.

6.5.4. Effect of loading rate

The impact of the loading rate has been evaluated under tensile and lap-shear loadings. Two speeds were considered, 0.01mm/sec and 1mm/sec. Two thicknesses (0.5mm and 1mm) were explored in each speed. Figure 6-31 shows the force-displacement curve of the lap shear test for the HDPE-McMaster-White substrates using the 3M-DP-8010 adhesive.
The results show that stiffness increases as the loading rate increases; however, the peak load is still the same, which indicates that the loading rate does not impact the bond strength. These results are depicted in Figure 6-32.

![Figure 6-31. Force vs Displacement using different loading rates.](image)

![Figure 6-32. Adhesive bond strength using different loading rates.](image)
6.5.5. **Effect of loading mode:**

Adhesives have been tested under two different loading modes, tensile and shear loads. Different substrates were considered, HDPE-McMaster-White and HDPE-Tangent-Gray. Figure 6-33 shows the force-displacement curve of the lap shear test for both substrates using the 3M-DP-8010 adhesive.

![Figure 6-33. Adhesive bond strength using different loading modes.](image)

<table>
<thead>
<tr>
<th></th>
<th>Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shear</strong> HDPE-Gray</td>
<td>7.58</td>
</tr>
<tr>
<td><strong>Tensile</strong> HDPE-Gray</td>
<td>5.12</td>
</tr>
<tr>
<td><strong>Shear</strong> HDPE-McMaster</td>
<td>2.58</td>
</tr>
<tr>
<td><strong>Tensile</strong> HDPE-McMaster</td>
<td>1.73</td>
</tr>
</tbody>
</table>

The results show that bond strength in the shear loading mode is approximately 30% higher than the bond strength in the tensile mode. The results also show that the bonding interlock is much better in shear loading.

6.5.6. **Failure mode:**

Butt-joint and Lap-shear tested specimens’ show mixed-mode failure, which consists of adhesion failure and HDPE-tear failure. Figure 6-34 and Figure 6-35 show the failure mode images of the specimens. The failure indicates that the adhesive bulk material is not failing, signifying that the adhesive is strong enough for this application.
Figure 6-34. Lap-shear tested specimen.

Figure 6-35. Butt-Joint tested specimen.
6.6. Computational Study

Finite element analysis has been utilized to further investigate the interface behavior between the structural adhesive and the HDPE substrate.

6.6.1. Mesh Model:

A full three-dimensional finite element model for butt-joint and lap-shear test specimens were modeled and simulated. The modeling software HyperMesh was used to build the mesh model using reduced-integration brick elements C3D8R with hourglass option were used for HDPE plates, Al plates and adhesive. ABAQUS solver was used to conduct the simulation. Kinematic constraints were used to apply displacement loading on the top hole and to fix the bottom hole as shown in Figure 6-36 and Figure 6-37.

Figure 6-36. Simulation model for lap shear test specimen.
Appropriate contact definitions were defined between the adhesive and the substrates, and two node sets were defined on the adhesives, one at the top surface and one at the bottom surface. The top node set of the adhesive was tied to the top substrate; the bottom node set was used in the surface interaction definition between the adhesive’s bottom surface and the bottom of the substrate.

6.6.2. **Cohesive Surface Modeling:**

The surface-based cohesive behavior is an interaction property between two substrates as shown in Figure 6-38.

Figure 6-37. Simulation model for butt-joint test specimen.

Figure 6-38. Cohesive surface interaction.
The formulae and laws that govern surface based cohesive behavior are as follows (ABAQUS 2014):

- Linear elastic traction-separation
- Damage initiation criteria
- Damage evolution laws

Figure 6-39. Schematic of traction-displacement.

Where,

- $t_n$: normal contact stress in the pure normal mode
- $t_s$: shear contact stress along the first shear direction
- $t_t$: shear contact stress along the second shear direction
- $\delta_n$: separation in the pure normal mode
- $\delta_s$: separation in the first shear direction
- $\delta_t$: separation in the second shear direction
The definition of the surface modeling is as follows (ABAQUS 2014):

- Linear elastic traction-separation (stiffness):

  \*SURFACE INTERACTION, NAME=cohesive

  \*COHESIVE BEHAVIOUR, ELIGIBILITY= ORIGINAL CONTACT \( \mathbf{K}_n; \mathbf{K}_s; \mathbf{K}_t \)

- Damage initiation criteria (failure limit):

  \begin{align*}
  \text{Maximum stress criterion} & : \quad \max \left\{ \frac{t_n}{t_n^{\max}}, \frac{t_s}{t_s^{\max}}, \frac{t_t}{t_t^{\max}} \right\} = 1 \\
  \text{Maximum separation criterion} & : \quad \max \left\{ \frac{\delta_n}{\delta_n^{\max}}, \frac{\delta_s}{\delta_s^{\max}}, \frac{\delta_t}{\delta_t^{\max}} \right\} = 1 \\
  \text{Quadratic stress criterion} & : \quad \left( \frac{t_n}{t_n^{\max}} \right)^2 + \left( \frac{t_s}{t_s^{\max}} \right)^2 + \left( \frac{t_t}{t_t^{\max}} \right)^2 = 1 \\
  \text{Quadratic separation criterion} & : \quad \left( \frac{\delta_n}{\delta_n^{\max}} \right)^2 + \left( \frac{\delta_s}{\delta_s^{\max}} \right)^2 + \left( \frac{\delta_t}{\delta_t^{\max}} \right)^2 = 1 \\
  
  \end{align*}

- Damage evolution laws

  \*DAMAGE EVOLUTION, TYPE=DISPLACEMENT or ENERGY \( \text{Value} \)

  \*CONTACT PAIR, INTERACTION=cohesive surface1, surface2
6.6.3. **Virtual Lap Shear Testing using FEA:**

Representative simulation models have been established for butt-joint and lap-shear test specimens to mimic the actual test. A convergence study was conducted to ensure that the solution can converge to the exact solution (according to experimental data results) with high accuracy. The following parameters have been accurately defined and optimized during the convergence study:

- Material models
- Mesh refinement
- P-refinement

Elastic-plastic material model has been used for Al plates, HDPE substrates and 3M-DP-8010 adhesive. Reduced-integration brick element C3D8R type has been used for all components, element size of 1mm was used for the substrate mesh and 0.5mm was used for the adhesive mesh. Adhesive mesh sensitivity study showed that two layers of elements across the width is needed to accurately capture the adhesive bulk and interface behavior.

<table>
<thead>
<tr>
<th>Material</th>
<th>Material Model</th>
<th>Element Type</th>
<th>Element size</th>
<th>Number of nodes</th>
<th>Number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>Elastic-plastic</td>
<td>C3D8R</td>
<td>1mm</td>
<td>528</td>
<td>300</td>
</tr>
<tr>
<td>Al</td>
<td>Elastic-plastic</td>
<td>C3D8R</td>
<td>1mm</td>
<td>25696</td>
<td>21520</td>
</tr>
<tr>
<td>Adhesive</td>
<td>Elastic-plastic</td>
<td>C3D8</td>
<td>0.5mm</td>
<td>35940</td>
<td>30204</td>
</tr>
</tbody>
</table>
Simulation successfully mimicked the delamination of the structural adhesive from the HDPE substrate during loading. Figure 6-40 show the simulated delamination during shear loading.

**Displacement contour @ zero load**

**Displacement contour @ peak load**

**Displacement contour @ complete failure**

Figure 6-40. Lap shear specimens at zero load, peak load and after failure.
Figure 6-41. Force-displacement comparison between lap-shear testing and simulation.

Figure 6-41 shows force-displacement comparison between lap-shear testing and simulation, reflecting good correlation between the results. Simulation mimics the stiffness, peak load, displacement and bond strength very well.
6.7. **Summary and Conclusions**

An experimental and numerical study that investigated the bond strength behavior of a structural adhesive was presented. Through the presented results which included different adhesives, substrates, thicknesses, loading modes and loading rates, the following conclusions were drawn:

- Structural adhesive bond strength to the HDPE substrate materials from “Tangent Technologies, LLC” supplier is twice stronger than to the ones purchased from “McMaster”. This is due to the skin layer which wets much better to the adhesive.

- 3M-DP-8010 bond strength to HDPE under butt-joint testing was 36% higher than the bond strength between the Loctite-3535 adhesive and the HDPE substrate.

- Thickness impacted bond strength where the 1mm-thick adhesive had 13% higher bond strength than the 0.5mm-thick adhesive. It is crucial to understand the adhesive interface behavior according to the geometrical conditions of the actual structural application.

- Loading rate impacted the stiffness of the overall sandwiched specimen; however, it did not impact the bond strength.

- Structural adhesives behaved stronger under shear loading where the bond strength was approximately 30% higher in shear loading than tensile loading.
7. ADHESIVELY BONDED HDPE COMPOSITE BEAMS

7.1. Introduction

In order to contribute to the development of an effective and reliable use of structural adhesives in the civil infrastructure applications, the allowable bond strength of adhesive bonded joints needs to be determined in order to design safe and efficient structures. In this study, experimental and computational studies have been conducted on bonded HDPE composite beams. The main objectives of this study are:

- To develop an understanding of the capabilities and limitations of adhesives in structural applications at a full-system level.
- To study the composite action of bonded HDPE beams.

The following section summarizes the material properties obtained from testing a system of adhesively-bonded HDPE beams:

7.1.1. Materials

7.1.1.1. HDPE

Recycled plastic HDPE beams have been used in this study. Mechanical properties of this material have been characterized under tensile loading according to ASTM-D630 standard. Stress-strain curves for HDPE under direct tensile testing are shown in Figure 7-1 and its mechanical properties are listed in Table 7-1.
7.1.1.2. Structural Adhesives

Two adhesives have been considered for this study:

- 3M-DP460
- 3M-DP8010

These two structural adhesives have been designed by 3M to provide high adhesion performance and a high level of durability. The bulk mechanical properties of these adhesives have been characterized under tensile loading according to ASTM-D630 standard.

Figure 7-2 shows the stress-strain curve of DP460 adhesive material, with mechanical property values listed in Table 7-2.
Figure 7-2. True stress-strain curve of DP460 adhesive material.

Table 7-2. Mechanical property of 3M-DP460 material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus [MPa]</th>
<th>Yield Stress [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M-DP460</td>
<td>2400</td>
<td>38</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Figure 7-3 shows the stress-strain curve of DP8010 adhesive material with mechanical property values in Table 7-3.

Figure 7-3. True stress-strain curve of 3M-DP8010.
Table 7-3. Mechanical property of 3M-DP8010 material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus [MPa]</th>
<th>Yield Stress [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M-DP8010</td>
<td>432</td>
<td>6.15</td>
<td>75</td>
</tr>
</tbody>
</table>

Table 7-4 summarizes the technical data that have been published by suppliers for these adhesive materials.

Table 7-4. Adhesives’ mechanical properties by suppliers.

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Chemical Type</th>
<th>Curing Time @ 22C</th>
<th>Time to handling strength @ 22C</th>
<th>Work Life @ 22C</th>
<th>Shear Strength using HDPE substrates @ 22C</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M-DP460</td>
<td>Two-part Epoxy adhesive</td>
<td>8-24 hrs</td>
<td>1.5-2 hrs</td>
<td>60 min</td>
<td>4 MPa</td>
</tr>
<tr>
<td>3M-DP8010</td>
<td>Two-part Acrylic adhesive</td>
<td>8-24 hrs</td>
<td>1.5-2 hrs</td>
<td>10-12 min</td>
<td>6 MPa</td>
</tr>
</tbody>
</table>

7.2. **Experimental Study**

Adhesively-bonded RPL beams were prepared to be tested under four point bending test and three point bending test to determine:

- Flexural behavior of the sandwiched beams structure.
- Failure limit and failure mode of the structural adhesive at the system level.

Two different sandwiched beams configurations were considered as shown in Figure 7-4:

- Equal-length-beam sandwich structure
- Unequal-length-beam sandwich structure
Configuration 1: Equal length beams

Beam: 38mmX152mmX1830mm
Adhesive: 1mmX5mmX1270mm [7 strips]

Configuration 2: Unequal length beams

Big Beam: 22mmX152mmX470mm
Small Beam: 22mmX152mmX140mm
Adhesive: 1mmX152mmX140mm

Figure 7-4. Equal-length-beam and unequal-length-plate sandwich structure configurations.

The equal-length-beam sandwich structure was tested under four-point bend test. The unequal-length-beam sandwich structure was tested under four-point bend test and three-point bend test with schematics of these tests are shown in Figure 7-5 to Figure 7-7.

Figure 7-5. Equal-length-beam sandwich structure under four-point bend loading.

Figure 7-6. Unequal-length-beam sandwich structure under four-point bend loading.
During each test, load, deflection, and strain data were collected and recorded by using a data logger. Two linear variable differential transducers (LVDTs) were placed at mid-span of the RPL specimen to measure deflection as shown in Figure 7-8. The load was supplied by means of a hydraulic loading system. The Load was applied at a rate of 0.25 in/min (6.35 mm/min) until ultimate load was reached.
7.2.1. Equal-length-beam sandwich structure

Sandwich beam structures were constructed where the structural adhesive was sandwiched between two RPL beams as shown in Figure 7-9. Two structural adhesives were considered in this study, 3M-DP-8010 and 3M-DP-460.

7.2.1.1. Specimens’ preparation

Two test specimens of equal-length-beam sandwich structures were prepared for a four point bend test. One specimen was adhered using DP460 and the other one was adhered using DP8010. Each specimen had two equal length beams, where each beam had the dimensions of 38mm x 152mm x 1830mm [T x W x L], that were bonded together using one of the two 3M structural adhesives.

DP460 requires substrate surface treatment in order to achieve good adhesion bond. Among different surface treatment methods, flame treatment was recommended based on data that has been published by 3M. Surface treatment was done in three stages:

- Cleaning the surface with 91% alcohol
- Etching the surface with sand paper then cleaning again with 91% alcohol
- Flame treatment then cleaning again with 91% alcohol

Figure 7-9 shows the equal-length-beam sandwich structure before and after adhesion. Seven strips of adhesive were applied on one of the beams in each sandwich structure; the dimension of each strip is 1mm x 5mm x 1270mm [T x W x L]. The beams were joined together and clamped for over 48 hrs.
DP8010 does not require a special surface treatment. It only requires the surface to be cleaned from any contamination which was done by using sand paper to etch the surface and then clean it with 91% alcohol.

7.2.2. Unequal-length-beam sandwich structure

Based on the equal-length-beam structure preliminary results, which will be shown in the next section, a decision was made to continue the study with the following modifications:

- Build unequal-length-beam structures, instead of equal-length-beam structure. Unequal-length-beam structures are capable of capturing mixed mode effects, whereas equal-length-beam specimen failed to capture the effect of mixed mode.
- Use only DP8010, as it showed promising results, with higher bond strength than DP460 and with no requirement for special surface treatment.
• Use different adhesive patterns (Figure 7-11) to capture the impact of adhesive geometry on the structural performance.

7.2.2.1. Specimens’ preparation

Five different configurations of unequal-length-beam structures were constructed for this study. The specimen dimensions are shown in Figure 7-10.

![Figure 7-10. Unequal-length-beam sandwich structure dimensions.](image)

Adhesive patterns of the five different configurations are shown in Figure 7-11. The black line colors represent the adhesive strips. Each strip of adhesive had a cross-section of 1mm x 6mm (thickness x width); the length of the strip is the length of the small plate. The adhesive strip’s thickness (1mm) was controlled by 1mm thick spacers as shown in Figure 7-12. The adhesive strip’s width was controlled by the nozzle opening which controls the volume of dispensed adhesive. Adhesive strips were spaced in an equal distances from each other.

The main reason of conducting the experiment using different configurations was to study the impact of the bonded adhesive area and the geometrical shape on the bond strength.
Figure 7-11. Adhesive patterns for the five different configurations.

Table 7-5 shows more details regarding the adhesive pattern and dimensions for each configuration.

<table>
<thead>
<tr>
<th></th>
<th>Type-I</th>
<th>Type-II</th>
<th>Type-III</th>
<th>Type-IV</th>
<th>Type-V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of strips</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Orientation</td>
<td>Vertical</td>
<td>Vertical</td>
<td>Vertical</td>
<td>6 Vertical</td>
<td>6 Horizontal</td>
</tr>
<tr>
<td>Dimension [mm]</td>
<td>1 x 6 x 140</td>
<td>1 x 6 x 140</td>
<td>1 x 6 x 140</td>
<td>V: 1 x 6 x 140</td>
<td>H: 1 x 6 x 150</td>
</tr>
</tbody>
</table>

All the test specimens were prepared and cured with the same conditions. Each specimen was clamped with four clamps as shown in Figure 7-12. All the specimens were cured for 48 hours.
7.3. Discussion of Experimental Results

7.3.1. Equal-length-beam sandwich structure

7.3.1.1. Equal-length-beam sandwich structure using 3M-DP-460 under 4-point bend:

DP460 sandwiched structure beams were loaded until failure as shown in Figure 7-13. The two plates were visually monitored at the sides and at the ends to detect any slippage between the plates. The beams were intact, slippage was not observed. The fracture occurred on the bottom beam as expected since it’s under tensile stresses. As soon as cracking occurs, the adhesive delaminated as shown in Figure 7-13c. After testing, it was...
easy to disassemble the two beams by hand which means the adhesive bond strength was weak, and it was easy to peel the adhesive from the beam as well, see Figure 7-13d.

Figure 7-13. Equal-length-beam sandwich structure using 3M-DP460 under 4-pnt bend test.

Force-deflection and stress-strain curves were extracted during testing. The results are shown in Figure 7-14 and Figure 7-15. Cracking occurred at 2.6% strain, with peak stress of about 1900 psi. Stress-strain curve dropped a bit as soon as the bottom beam cracked.
Figure 7-14. Load – Deflection curve of equal-length-beam sandwich structure using 3M-DP460.

Figure 7-15. Stress-Strain curve of equal-length-beam sandwich structure using 3M-DP460.

7.3.1.2. Equal-length-beam sandwich structure using 3M-DP-8010 under 4-point bend:

DP8010 sandwiched structure beams were loaded until failure as shown in Figure 7-16. The two plates were visually monitored at the sides and at the ends to detect any slippage between the plates. The beams were intact, slippage was not observed. The fracture
occurred on the bottom beam and then propagated to the top beam as shown in Figure 7-16c.

Adhesive did not propagate beyond the cracking area as can be seen in Figure 7-16d.

Figure 7-16. Equal-length-beam structure using 3M-DP8010 under 4-point bend test.
Disassembling the two beams was hard which means that the adhesive bond strength was strong. While disassembling the two beams, the adhesive pulled off material from the beam which is a good indication of having good adhesion and cohesion failure limits. Figure 7-17 shows snapshots of the beams during and after disassembly.

![Disassembled beams](image)

Figure 7-17. Equal-length-beam structure using 3M-DP8010 after 4-point bend test.

Force-deflection and stress-strain curves were extracted during testing. The results are shown in Figure 7-18 and Figure 7-19. Cracking occurred at 3.5% strain with peak stress of about 2100 psi. Both beams cracked simultaneously.
Figure 7-18. Load – Deflection curve of equal-length-beam sandwich structure using 3M-DP8010.

Figure 7-19. Stress-Strain curve of equal-length-beam sandwich structure using 3M-DP8010.
7.3.2. Unequal-length-beam sandwich structure

The five different adhesive patterns were tested under, four-point bend and three-point bend, resulting in a total of 10 different configurations. The HDPE beams used in all ten configurations were from the same supplier but from different lots and had different colors. For configurations I, II and III, the HDPE beams were obtained from the same lot and were gray in color. For configurations IV and V, the HDPE beams were obtained from another lot and were red in color. The HDPE beams, both gray and red, behaved the same in testing, which indicated that they had the same material and mechanical properties.

7.3.2.1. Unequal-length-beam sandwich structure using 2 strips of 3M-DP-8010 under 4-point bend

The adhesive pattern in this configuration had two strips of adhesive and covered 8% of the total area between the small beam and the big beam. The structural adhesive delaminated from both sides, as shown in Figure 7-20, indicating mixed-mode failure, which consisted of adhesion failure and HDPE-tear failure. The results signify that the adhesive bulk material is not failing and that it is strong enough for this application.

Figure 7-20. Unequal-length-beam sandwich structure using 2 strips of 3M-DP-8010 under 4-point bend.
Figure 7-21 shows the force displacement test results. Adhesive delamination started approximately at 1600N.

![Force-deflection curve](image)

**Figure 7-21.** Force-deflection curve for Unequal-length-beam sandwich structure using 2 strips of 3M-DP-8010 under 4-point bend.

7.3.2.2. Unequal-length-beam sandwich structure using 4 strips of 3M-DP-8010 under 4-point bend

The adhesive pattern in this configuration had four strips of adhesive and covered 16% of the total area between the small beam and the big beam. The structural adhesive delaminated from both sides, as shown in Figure 7-22, indicating mixed-mode failure, which consisted of adhesion failure and HDPE-tear failure. Cohesion failure was not observed during testing.
Figure 7-22. Unequal-length-beam sandwich structure using 4 strips of 3M-DP-8010 under 4-point bend.

Figure 7-23 shows force displacement test results. Adhesive delamination started approximately at 2730N.

Figure 7-23. Force-deflection curve for Unequal-length-beam sandwich structure using 4 strips of 3M-DP-8010 under 4-point bend.
7.3.2.3. Unequal-length-beam sandwich structure using 6 strips of 3M-DP-8010 under 4-point bend

Figure 7-24. Unequal-length-beam sandwich structure using 6 strips of 3M-DP-8010 under 4-point bend.

The adhesive pattern in this configuration had six strips of adhesive and covered 24% of the total area between the small beam and the big beam. The structural adhesive delaminated on one side, as shown in Figure 7-24, indicating mixed-mode failure, which consisted of adhesion failure and HDPE-tear failure. Cohesion failure was not observed during testing. Figure 7-25 shows force displacement test results. Adhesive delamination started approximately at 2730N.

Figure 7-25. Force-deflection curve for Unequal-length-beam sandwich structure using 6 strips of 3M-DP-8010 under 4-point bend.
7.3.2.4. Unequal-length-beam sandwich structure using 12 strips of 3M-DP-8010 under 4-point bend

The adhesive pattern in this configuration had twelve strips of adhesive and covered 48% of the total area between the small beam and the big beam. The structural adhesive did not delaminate. Figure 7-26 shows that the upper beam started to crack without noticing any adhesive delamination.

Figure 7-26. Unequal-length-beam sandwich structure using 12 strips of 3M-DP-8010 under 4-point bend.

Figure 7-27 shows force displacement test results. Full composite action was observed with peak load of 4576N.

Figure 7-27. Force-deflection curve for Unequal-length-beam sandwich structure using 12 strips of 3M-DP-8010 under 4-point bend.
7.3.2.5. Unequal-length-beam sandwich structure using full area adhesive of 3M-DP-8010 under 4-point bend

The adhesive pattern in this configuration covered the 100% of the area between the small beam and the big beam. The structural adhesive did not delaminate. Figure 7-28 shows that the upper beam started to crack without noticing any adhesive delamination.

Figure 7-28. Unequal-length-beam sandwich structure using full area adhesive of 3M-DP-8010 under 4-point bend.

Figure 7-29 shows force displacement test results. Full composite action was observed with peak load of 4654N.

Figure 7-29. Force-deflection curve for Unequal-length-beam sandwich structure using full area adhesive of 3M-DP-8010 under 4-point bend.
Figure 7-30 shows the Force-deflection curves for the different configurations under 4-point bend loading. As expected less bonding area provides less bonding strength. The specimens with less bonding area started delamination earlier. Configuration-IV and configuration-V had almost the same peak force, which indicated that one can get the same strength with less adhesive consumption.

Figure 7-30. Force-deflection curve for the different configurations under 4-pnt bend
7.3.2.6. Unequal-length-beam sandwich structure using 2 strips of 3M-DP-8010 under 3-point bend

The adhesive pattern in this configuration had two strips of adhesive, it covered 8% of the total area between the small beam and the big beam. The structural adhesive delaminated from both sides, as shown in Figure 7-31, indicating mixed mode failure, which consisted of adhesion failure and HDPE-tear failure. The results signify that the adhesive bulk material is not failing and that it is strong enough for this application. Figure 7-32 shows force displacement test results. Adhesive delamination started at ~1500N.

Figure 7-31. Unequal-length-beam sandwich structure using 2 strips of 3M-DP-8010 under 3-point bend.

Figure 7-32. Unequal-length-beam sandwich structure using 2 strips of 3M-DP-8010 under 3-point bend.
7.3.2.7. Unequal-length-beam sandwich structure using 4 strips of 3M-DP-8010 under 3-point bend

The adhesive pattern in this configuration had four strips of adhesive and covered 16% of the total area between the small beam and the big beam. The structural adhesive delaminated from both sides, as shown in Figure 7-33, indicating mixed mode failure, which consisted of adhesion failure and HDPE-tear failure. Cohesion failure was not observed during testing. Figure 7-34 shows force displacement test results. Adhesive delamination started approximately at 1950N.

Figure 7-33. Unequal-length-beam sandwich structure using 4 strips of 3M-DP-8010 under 3-point bend.

Figure 7-34. Force-deflection curve for Unequal-length-beam sandwich structure using 4 strips of 3M-DP-8010 under 3-point bend.
7.3.2.8. Unequal-length-beam sandwich structure using 6 strips of 3M-DP-8010 under 3-point bend

The adhesive pattern in this configuration had six strips of adhesive and covered 24% of the total area between the small beam and the big beam. The structural adhesive delaminated from both sides, as shown in Figure 7-35, indicating adhesive mixed mode failure, which consisted of adhesion failure and HDPE-tear failure. Cohesion failure was not observed during testing. Figure 7-36 shows force displacement test results. Adhesive delamination started approximately at 3000N.

Figure 7-35. Unequal-length-beam sandwich structure using 6 strips of 3M-DP-8010 under 3-point bend.

Figure 7-36. Unequal-length-beam sandwich structure using 6 strips of 3M-DP-8010 under 3-point bend.
7.3.2.9. Unequal-length-beam sandwich structure using 12 strips of 3M-DP-8010 under 3-point bend

The adhesive pattern in this configuration had twelve strips of adhesive and covered 48% of the total area between the small beam and the big beam. The structural adhesive did not delaminate. Figure 7-37 shows that the upper beam started to crack without noticing any adhesive delamination. Figure 7-38 shows force displacement test results, with almost full composite action observed and peak load of 4490N.

![Figure 7-37. Unequal-length-beam sandwich structure using 12 strips of 3M-DP-8010 under 3-point bend.](image1)

![Figure 7-38. Force-deflection curve for Unequal-length-beam sandwich structure using 12 strips of 3M-DP-8010 under 3-point bend.](image2)
7.3.2.10. Unequal-length-beam sandwich structure using full area adhesive of 3M-DP-8010 under 3-point bend

The adhesive pattern in this configuration covered the 100\% of the area between the small beam and the big beam. The structural adhesive did not delaminate. Figure 7-39 shows that the upper beam started to crack without noticing any adhesive delamination. Figure 7-40 shows force displacement test results and full composite action was observed with peak load of 4650N.

Figure 7-39. Unequal-length-beam sandwich structure using full area adhesive of 3M-DP-8010 under 3-point bend.

Figure 7-40. Force-deflection curve for Unequal-length-beam sandwich structure using full area adhesive of 3M-DP-8010 under 3-point bend.
Figure 7-41 shows the Force-deflection curves for the different configurations under 3-pnt bend loading. As expected, less bonding area results in less bonding strength. The specimens with less bonding area started delamination earlier. Configuration-IV and configuration-V had almost the same peak force, which indicated that one can get the same strength with less adhesive consumption.

Figure 7-41. Force-deflection curve for the different configurations under 3-pnt bend loading.

Comparing the 3-point bend test results to the 4-point bend test results that we discussed in the previous section, we can see that the same configuration would fail sooner in 3-point bend. This is due to the fact that the load is localized at the edge in 3-point bend as opposed to a more distributed load in 4-point bend.
7.4. **Computational Study**

Finite element analysis has been utilized to further investigate the behavior of bonded HDPE beams under three-point bend testing and to correlate it with the experimental behavior. To establish this correlation, there is no need to simulate all the experimentally tested configurations. Therefore, only two configurations were selected for computational study which are:

- Unequal-length-beam sandwich structure using full area adhesive of 3M-DP-8010 under 3-point bend.
- Unequal-length-beam sandwich structure using 6 strips of 3M-DP-8010 under 3-point bend.

7.4.1. **Mesh Model:**

A full three-dimensional finite element model for unequal-length-beam sandwich structure was modeled and simulated. The modeling software HyperMesh was used to build the mesh model using reduced-integration brick elements C3D8R with hourglass option for the HDPE beams and the adhesive. The ABAQUS solver was used to conduct the simulation.
Figure 7-42. Mesh model of unequal-length-beam sandwich structure.

Figure 7-43. Simulation model of unequal-length-beam sandwich structure.
Similar to previous models, boundary conditions and contact definitions were applied accordingly to simulate the support and the contact. The following are the boundary condition definitions for the rollers:

- **TOP-FIXTURE, 1, 2, 0.0**  
  [U1 and U2 are fixed]
- **TOP-FIXTURE, 3, 3, 15**  
  [U3 assigned to move by 15mm]
- **TOP-FIXTURE, 4, 6, 0.0**  
  [U4, U5 and U6 are fixed]
- **BOTTOM-FIXTURE-REF, 1, 6, 0.0**  
  [All degree of freedom are fixed]

7.4.1.1. Simulation of unequal-length-beam sandwich structure using Full adhesive (configuration-V)

Figure 7-44. Simulation model of unequal-length-beam sandwich structure (Type V).

Figure 7-45. Simulation model of full adhesive during 3-pnt bend loading.
Figure 6-41 shows a comparison between the numerical and experimental results. The results show very good correlation. A representative simulation model utilizing cohesive surface modeling was able to mimic adhesive behavior accurately, it confirm that 3M-DP8010 adhesive with full bond area is capable to withstand the shear and tensile forces during 3-point-bend testing without delaminating.
7.4.1.2. Simulation of unequal-length-beam sandwich structure using partial adhesive (configuration-III)

Figure 7-47. Simulation model of unequal-length-beam sandwich structure (Type III).

Figure 7-48. Simulation model of partial adhesive during 3-pnt bend loading.
Figure 7-49. Force-deflection curve comparison between simulation and testing – Type III.

Figure 6-41 shows a comparison between the numerical and experimental results for type-III configuration under 3-point-bend testing. The results show very good correlation. A representative simulation model utilizing cohesive surface modeling was able to mimic adhesive failure limit and behavior up until delamination very well. Damage evolution was not part of this study; hence we did not attempt to predict adhesive damage propagation.
7.5. SUMMARY AND CONCLUSIONS

An experimental and numerical study that investigated the bond strength behavior of structural adhesive for HDPE beams at system level was presented. Through the presented results which included different adhesives materials, different adhesive patterns, different loading cases substrates, the following conclusions were drawn:

- Although the 3M-DP460 adhesive had a stiffness that is 6 times higher than the 3M-DP8010 adhesive, it yielded poor results in testing due to the lower surface bond. Furthermore, 3M-DP460 required surface treatment which might not be practical in big structural applications.

- Adhesive patterns affected the bond strength results; increasing bonded area increased the bond strength. However, after covering 48% of the interface area, the increase of adhesive area did not change the results. Understanding the adhesive bonding limit and the serviceability of the overall system help optimize the amount of adhesive to be used, resulting in cost savings and reduced curing time.

- Mixed mode failure was observed in all failed samples, including adhesion failure and HDPE-tear failure, which signified that the adhesive bulk material is not failing and that the adhesive was strong enough for this application.

- Simulation results correlated very well with testing results, simulation model can be used to further optimize the adhesive pattern design and area to meet specific application needs.
8. SUMMARY AND CONCLUSIONS

The technical assessment presented in this study showed that the recycled plastic material can be designed for structural application and can substitute the reinforced concrete and wood materials in several structural applications.

Life cycle cost assessment showed that the reinforced recycled plastic material has great environmental benefit and that greenhouse gases emissions are much lower when using the recycled plastic material for construction compared to concrete and wood materials.

The recycled plastic beam cost was lower than the reinforced concrete beams but higher than wooden beams. Although it is higher than the cost of wooded beam, previous studies showed that maintenance requirements and cost over the life cycle of the recycled plastic beam is much lower than that of the concrete and wooden beams.

Using recycled plastic as a structural material has the highest score in all social dimensions. It reduces deforestation by substituting wood in many applications, reduces solid wastes at landfill, requires less maintenance, and retains new look for longer time.

Recycled plastic lumbers (RPLs) beams were studied experimentally and computationally to investigate the structural behavior and mechanical properties of RPL beams. The parameters tested were the cross-sectional area of the GFRP reinforcement, strong versus weak axis of the RPL, span length, and recycled plastic mix. The following conclusions and recommendations can be made based on the findings:
Addition of GFRP reinforcement bars is more effective than addition of additives to the recycle plastic material to increase the ultimate load capacity and the stiffness of the Plastic beams.

The stiffness of the recycled plastic beams increased linearly with the increase of area of GFRP rods.

The ultimate load capacity can be increased about 5 times and the stiffness can be increased about 3 times while decreasing the deflection about 40% by increasing the GFRP reinforcement area.

It is very advantageous to increase the load capacity and the stiffness by increasing the reinforcement area after finalizing and/or selecting the best suitable recycle plastic mix. Using a stiffer recycle plastic mix may not allow the GFRP to be fully stressed as recycle plastic may fail before fully utilizing the GFRP reinforcement.

Virtual testing can be achieved through simulation, where we can optimize the design strength with much less time and cost.

Elastoplastic analysis using finite element models can be used for accurate prediction of the tensile stress-strain behavior of composites.

Different beam shapes (I-beam & hollow beam) can be used instead of full beam with comparable stiffens results (90%-95%) and with much better manufacturing advantages (lower weight, less material, faster cooling …etc).
A numerical and experimental study that investigated the behavior of a structural adhesive under quasi-static and dynamic loading was presented. Through the presented results which are specific to the sandwich structure materials used in this study, the following conclusions can be drawn:

- The sandwich structure with unequal-length plates is able to capture the sensitivity to the adhesive material modeling approaches. However, the sandwich structure with equal-length plates is insensitive to the adhesive layer and failed as a configuration for capturing or investigating adhesive behavior and properties.

- Comparison between numerical and experimental results from both the quasi-static and dynamic simulation results show that the elastic-plastic material model mimics the adhesive material behavior better than the elastic material models, due to the ability of the elastic-plastic model to account for adhesive plasticity.

- Although both of the elastic and plastic phases of this specific adhesive are loading rate dependent, plastic behavior of the adhesive has bigger impact than its elastic behavior on the overall sandwich structure behavior. This is due to the fact that the adhesive will start deforming while the adhered substrates are still in their elastic regions.

An experimental and numerical study that investigated the bond strength behavior of a structural adhesive was presented. Through the presented results which included different adhesives, substrates, thicknesses, loading modes and loading rates, the following conclusions were drawn:
o Structural adhesive bond strength to the HDPE substrate materials from “Tangent Technologies, LLC” supplier is twice stronger than to the ones purchased from “McMaster”. This is due to the skin layer which wets much better to the adhesive.

o 3M-DP-8010 bond strength to HDPE under butt-joint testing was 36% higher than the bond strength between the Loctite-3535 adhesive and the HDPE substrate.

o Thickness impacted bond strength where the 1mm-thick adhesive had 13% higher bond strength than the 0.5mm-thick adhesive. It is crucial to understand the adhesive interface behavior according to the geometrical conditions of the actual structural application.

o Loading rate impacted the stiffness of the overall sandwiched specimen; however, it did not impact the bond strength.

o Structural adhesives behaved stronger under shear loading where the bond strength was approximately 30% higher in shear loading than tensile loading.

An experimental and numerical study that investigated the bond strength behavior of structural adhesive for HDPE beams at system level was presented. Through the presented results which included different adhesives materials, different adhesive patterns, different loading cases substrates, the following conclusions were drawn:

o Although the 3M-DP460 adhesive had a stiffness that is 6 times higher than the 3M-DP8010 adhesive, it yielded poor results in testing due to the lower surface bond. Furthermore, 3M-DP460 required surface treatment which might not be practical in big structural applications.

o Adhesive patterns affected the bond strength results; increasing bonded area increased the bond strength. However, after covering 48% of the interface area, the
increase of adhesive area did not change the results. Understanding the adhesive bonding limit and the serviceability of the overall system help optimize the amount of adhesive to be used, resulting in cost savings and reduced curing time.

- Mixed mode failure was observed in all failed samples, including adhesion failure and HDPE-tear failure, which signified that the adhesive bulk material is not failing and that the adhesive was strong enough for this application.

- Simulation results correlated very well with testing results, simulation model can be used to further optimize the adhesive pattern design and area to meet specific application needs.
9. SUGGESTIONS FOR FUTURE RESEARCH

The study has been carried under tensile and shear loading at normal environmental conditions. There are different loading scenarios and environmental condition that should be investigated in order to understand the behavior of joint adhesives under extreme loading conditions, such:

- Creep loading and fatigue loading scenarios - since civil infrastructure applications are expected to last for many years of use where the structure will be constantly loaded and unloaded, it is crucial to investigate adhesive’s joint behavior under such loading scenarios.
- Extreme temperature and humidity environmental conditions – understanding the impact of these conditions is crucial since they can conspicuously impact the adhesive bulk behavior as well as the interface behavior.

Adhesive substrate surface texture needs further investigation in order to be optimized in a way it they can be factored in the design to contribute to the highest bond strength possible:

- HDPE-beam’s substrate surface texture should be investigated and optimized; it may contribute to the bonding failure if it is not designed and optimized properly.

Surface based cohesive behavior method in ABAQUS has been used successfully to mimic adhesive stiffness and damage initiation in this study; however, we did not attempt to capture the damage evolution of the adhesive.

- Damage evolution laws and methods should be investigated to be able to predict adhesive damage propagation.
CITED REFERENCES


- PlasticsEurope. Distribution of European plastic consumption according to its nature in millions of tons per year, Caudron, 2003; 2011.


- Simulia, ABAQUS Documentation, version 6.14, 2014

- SimaPro 8.0 LCA package


APPENDIX-A

This appendix presents the 3M-DP8010 technical datasheet at uncured and cured state which has been published by the supplier (3M):

Table A-1: 3M-DP-8010 Uncured Properties.

<table>
<thead>
<tr>
<th>Product</th>
<th>3M™ Scotch-Weld™ Structural Plastic Adhesive DP-8010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>Pink/Amber White</td>
</tr>
<tr>
<td>Lbs./gal.</td>
<td>Base (B) Accelerator (A)</td>
</tr>
<tr>
<td></td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
</tr>
<tr>
<td>Viscosity (cps)(1)</td>
<td>Base (B) Accelerator (A)</td>
</tr>
<tr>
<td></td>
<td>17,000</td>
</tr>
<tr>
<td></td>
<td>27,000</td>
</tr>
<tr>
<td>Base Resin</td>
<td>Base (B) Accelerator (A)</td>
</tr>
<tr>
<td></td>
<td>Methacrylate Amine</td>
</tr>
<tr>
<td>Mix Ratio</td>
<td>(Volume)</td>
</tr>
<tr>
<td></td>
<td>10:1</td>
</tr>
<tr>
<td></td>
<td>(Weight)</td>
</tr>
<tr>
<td></td>
<td>9.8:1</td>
</tr>
<tr>
<td>Time to Handling Strength (minimum of 50 psi of shear at 73°F/23°C)</td>
<td>1.5 - 2 hrs.</td>
</tr>
<tr>
<td>Full Cure 73°F (23°C)</td>
<td>8 - 24 hrs.</td>
</tr>
<tr>
<td>Worklife 73°F (23°C)</td>
<td>10 - 12 min.</td>
</tr>
</tbody>
</table>

Table A-2: 3M-DP-8010 Cured Properties.

<table>
<thead>
<tr>
<th>Product</th>
<th>Scotch-Weld adhesive DP-8010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>Yellow</td>
</tr>
<tr>
<td>Tg onset (*°C)(2)</td>
<td>34</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion (ppm°°C)(2)</td>
<td></td>
</tr>
<tr>
<td>Below Tg</td>
<td>133</td>
</tr>
<tr>
<td>Above Tg</td>
<td>171</td>
</tr>
<tr>
<td>Mechanical Properties(3)</td>
<td>Strain at Break</td>
</tr>
<tr>
<td></td>
<td>Stress at Break (psi)</td>
</tr>
<tr>
<td></td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>1,900</td>
</tr>
<tr>
<td></td>
<td>Modulus @ 1% Strain (psi)</td>
</tr>
<tr>
<td></td>
<td>70,000</td>
</tr>
</tbody>
</table>
APPENDIX-B

This appendix presents the Loctite-3035 technical datasheet at uncured and cured state which has been published by the supplier (Henkel):

Table B-1: Loctite-3035 Uncured Properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix Ratio</td>
<td>1:1</td>
</tr>
<tr>
<td>Viscosity</td>
<td>7,500 cP (Part A), 60,000 cP (Part B)</td>
</tr>
<tr>
<td>Sustainability</td>
<td>halogen-free, non-flammable, low outgassing</td>
</tr>
<tr>
<td>Odor</td>
<td>mild</td>
</tr>
</tbody>
</table>

Table B-2: Loctite-3035 Cured Properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>pale yellow</td>
</tr>
<tr>
<td>Working Time, min</td>
<td>4</td>
</tr>
<tr>
<td>Fixture Time, min</td>
<td>&gt;10&lt;15 (HDPE), &gt;10&lt;15 (HDPE/Steel)</td>
</tr>
<tr>
<td>Surface Cure</td>
<td>pass (24 hr. closed container)</td>
</tr>
<tr>
<td>Shrinkage (read-thru)</td>
<td>not tested</td>
</tr>
</tbody>
</table>

Table B-3: Loctite-3035 Mechanical Cured Properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength (ksi)</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polyolefins</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HDPE</td>
<td>1658</td>
<td>11.5</td>
</tr>
<tr>
<td>HDPE/Steel</td>
<td>657</td>
<td>4.56</td>
</tr>
<tr>
<td>LDPE</td>
<td>632</td>
<td>4.41</td>
</tr>
<tr>
<td><strong>Metals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>879</td>
<td>6.00</td>
</tr>
<tr>
<td>Aluminum</td>
<td>423</td>
<td>2.91</td>
</tr>
<tr>
<td><strong>Other Plastics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABS</td>
<td>642</td>
<td>4.44</td>
</tr>
<tr>
<td>Acrylic</td>
<td>886</td>
<td>6.07</td>
</tr>
<tr>
<td>Delrin</td>
<td>120</td>
<td>0.83</td>
</tr>
<tr>
<td>G-10 Epoxy</td>
<td>1045</td>
<td>7.21</td>
</tr>
<tr>
<td>Nylon</td>
<td>226</td>
<td>1.56</td>
</tr>
<tr>
<td>PC</td>
<td>726</td>
<td>5.03</td>
</tr>
<tr>
<td>Phenolic</td>
<td>416</td>
<td>2.85</td>
</tr>
<tr>
<td>PVC</td>
<td>1237</td>
<td>8.52</td>
</tr>
<tr>
<td>Valox 420</td>
<td>1081</td>
<td>7.42</td>
</tr>
</tbody>
</table>
Recycled Plastic lumber (RPL) has been used as a substrate material, it manufactured from purified blends of post-consumer, pre-consumer, additives and virgin high density polyethylene (HDPE). Material analysis has been conducted to understand the compound and the additive geometry and distribution using SEM/EDX optical technique. Results show the following:

Figure C-1: SEM image of RPL mix away from the skin (zoom level 42x).

Figure C-2: SEM image of RPL mix away from the skin (zoom level 200x).
Figure C-3: SEM image of RPL mix away from the skin (zoom level 1502x).

Figure C-4: RPL material composition away from the skin.
Figure C-5: SEM image of the skin of the RPL beam (zoom level 40x).

Figure C-6: RPL material composition for the skin.

Table C-1: Technical data that has been published by supplier.
### Table C-1: Physical and Chemical Characteristics.

<table>
<thead>
<tr>
<th>Property</th>
<th>ASTM Method</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>D6111-13</td>
<td>lbs/in³</td>
<td>0.0215-0.030*</td>
</tr>
<tr>
<td>Water Absorption</td>
<td>D570-05</td>
<td>%</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Secant Modulus @ 1% Strain**</td>
<td>D6109-05</td>
<td>psi</td>
<td>137,861***</td>
</tr>
<tr>
<td>Stress @ 3% Strain**</td>
<td>D6109-05</td>
<td>psi</td>
<td>2,114***</td>
</tr>
<tr>
<td>Screw Withdrawal</td>
<td>D6117-97</td>
<td>lbf</td>
<td>703</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>D6341-98</td>
<td>in/in°f</td>
<td>0.0000281</td>
</tr>
</tbody>
</table>

**Flexural Property**

### Appearance
Non-Translucent, Colored Extruded product

### Odor
Slight

### Boiling Point
N/A

### Melting Point
250°F  121°C

### Vapor Pressure (mm HG)
N/A

### Specific Gravity (H2O = 1), (g/cc)
0.65 – 0.88

### Solubility in Water
Negligible

### Evaporative Rate
Negligible

### Vapor Density (air = 1)
N/A

### Evaporation Point
N/A