ARIZONA STATE UNIVERSITY

SCHOOL OF SUSTAINABLE ENGINEERING AND THE BUILT ENVIRONMENT

CESEM

Center for Earth Systems Engineering and Management

# The Comparative Life Cycle Assessment of Structural Retrofit Techniques

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***Contents***

# Attributional Comparative LCA for Structural Retrofit/ Strengthening Techniques

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**Executive Summery**

The current study conducts a comparative LCA of two alternative structural retrofit/ strengthening techniques - steel jacketing, and the carbon fiber reinforced polymer (CFRP) retrofit. A cradle-to-gate system boundary is used for both techniques. The results indicated that the CFRP retrofit technique has merits over the conventional steel jacketing in all three impact categories covered by this study. This is primarily attribute to the much less material consumption for CFRP retrofit as compared to steel jacketing for achieving the same load carrying capability of the retrofitted bridge structures. Even though the transoceanic transportation of carbon fiber has been taken into account in this study, the energy consumption and environmental impacts of CFRP transportation is still much smaller than steel due to it light weight property. The impacts of CFRP retrofit are mainly focused in the material manufacturing phase, which implies that the improvements in the carbon fiber manufacturing technology could potentially further reduce the environmental impacts of CFRP retrofit.

## 1. Introduction and Back Ground

### *1.1 Structural deteriorations and the strengthening/ retrofit techniques*

Civil infrastructure systems degrade while subject to hazardous environments or load conditions. Structural damages can be induced by many sources like natural disasters (earthquake, tornado etc.), environments, hazardous load conditions (fatigue, impacts etc.), or the property degradation of construction materials themselves. The environmental deterioration of civil infrastructures has caused significant economic impacts. Many studies [1-3] have indicated that a enormous amount of highway bridges, as shown in Figure 1, have experienced fatigue and other types of damages. Many construction materials, such as steel, are prone to environmental degradation. Figure 2 shows a bridge located at Akron, OH experiences extensive corrosion problem. Upon damage, it is often very costly, or even not possible in some cases, to demolish and reconstruct the damaged structures. Instead of costly demonishing and reconstruction, the structural retrofitting and repairing techniques provide alternatives with significant economic benefit.

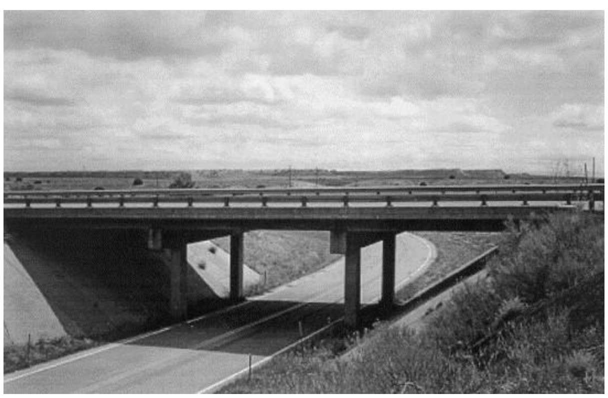

**Figure 1. A typical high way bridge in US**

**Figure 2. Corroded steel bridge girders**
(Photo courtesy of Termarust Tech) [4]

Generally, two categories of retrofit techniques that have been used over the years are currently availuable in the construction market: one category is the conventional retrofit techniques including steel/ concrete jacketing (as shown in Figure 3), section enlargement etc.; and another retrofitting option that has been gaining popularity has been the use of externally bonded polymer matrix composites (PMCs) [5] such as carbon fiber reinforced polymers (CFRPs), see Figure 4. Most PMC materials provide a high strength-to-density ratio, excellent resistance to environmental deterioration, and they are easy to implement on-site.

Extensive studies have been conducted on fiber reinforced polymers (FRP) in the repair reinforced concrete structures in experimental [5 – 11] and field applications [7]. FRP-strengthening and application of retrofitting techniques of steel structures have also started to increase in popularity in recent years [8].

**Figure 3. Steel jacketing retrofit of a beam in a building**

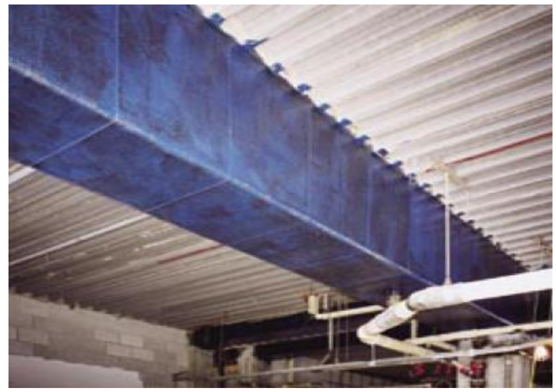

**Figure 4. Picture showing beam retrofit using CFRP**

The proposed project seeks the way to assess the economical and environmental impacts of the two alternative methods of repairing/ retrofit of civil infrastructure systems. The energy and environmental factors involved in the process of material manufacturing, transportation, and on-site implementation will be tracked and assessed. The actual material usage for the CFRP retrofitting will be based upon ealier studies on the mechanical performance of the retrofitted structures [5], and the results will be projected to a typical two-lane highway bridge in the United States, as shown in Figure 1. The material usage for the steel jacketing will be calculated based on the function unit selected for the two alternative retrofitting strategies). The **energy consumption** and **environmental impacts**, such as green house gases (GHGs) emission, will be compared in order to assist the bridge owners to make critical decisions.

## 2. System Boundary, Elementary Flow and Data Resources

Since the durability, or environmental degradation, issue and waste management for the carbon-fiber reinforced composite materials have not been extensively studied thus far, a "Cradle-to-Gate" boundary is selected for both retrofitting strategies, i.e. the assessments start from the raw material extraction and terminate when the retrofitting systems are "ready to use". In this light, the processes that are considered in this study include the extraction and production of raw materials (iron ore for steel jacketing, and oil products, such as ammonia, for carbon fiber, and the associate polymers); material refinery (steel) and synthesis (carbon fiber); transportation of materials; and lastly, the in-situ implementation of both retrofitting systems.  A initial flow chart that includes the  most essential processes within the scope of this study is presented in Figure 5.  Please note the processess that are contained in the solid box are those have been included in this study; and the processes in the dashed box are the ones that have been leaved out.

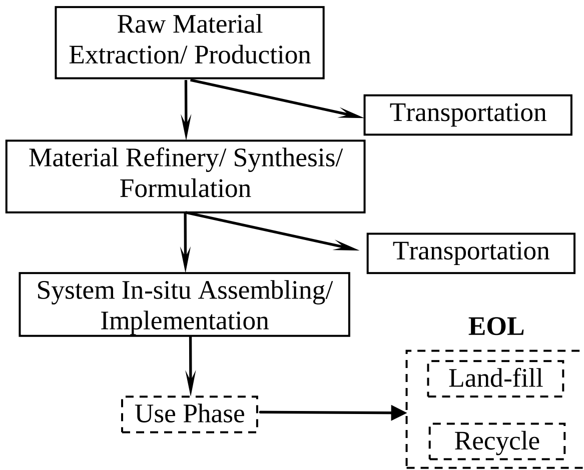


**Figure 5. Initial flow chart showing the life cycle of structural retrofitting systems**

*2.1 Steel jacketing retrofit/ strengthening*

The steel jacketing retrofit for beams subject to bending is to bond steel plates to the bottom of the existing beam in order to increase their flexural load capacities.  For the retrofit of reinforced concrete bridge girders, such as the ones shown in Figure 1, either epoxy-based glue or mechanical anchors can be used to mount the steel plates.  Before the plate the mounting, the beam surfaces usually have to be sand-blasted and cleaned in order to develop and good bonding strength.  Figure 6 shows a illustrative figure of the steel jacketing and the elementary low of the steel jacketing retrofit process.  It starts form the raw material extration, and ends at the ready-to-use of the retrofit system.  The transportation for both raw mateirals and the final products have been included in this study, however, due to the lack of information, the material storage at contractor's site has been left out.

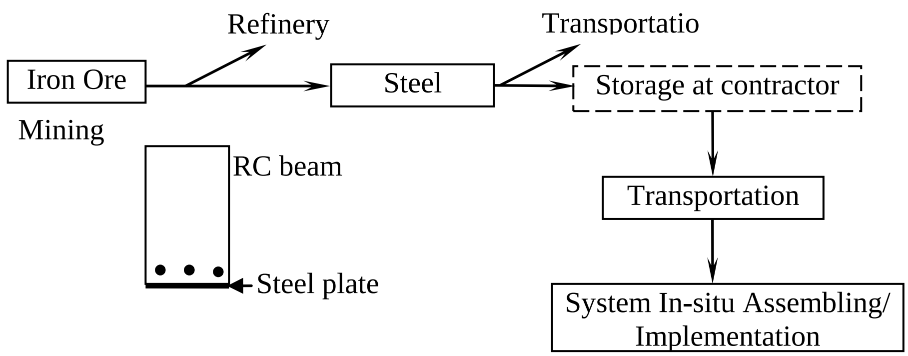


**Figure 6. Elementary Flow of Steel Jacketing (Cradle to Gate)**

*2.2 Structural retrofit using carbon fiber reinforced polymers (CFRPs)*

The processes involved in the carbon fiber reinforced polymer (CFRP) manufacturing and implementation are presented in Figure 7. The carbon fibers are produced from fiber precursors such as polyacrylonitrile, or PAN. PAN is a polymerization product of Acrylonitrile, and the Acrylonitrile is produced by the Sohio process [12]. For synthezing 1kg of Acrylonitrile, 0.4 kg ammonia and 1 kg of propylene would be needed. Though extensive studies and researches have been conducted on carbon fiber and its composite materials, the ones that report the resources/ energy comsumptions and the envrionmental impacts during the manufacturing stages are very rare. Based on a recent study at University of Tokyo by Zhang et al. [13], the total energy consumption associated in manufacturing 1 kg of carbon fiber is 286 MJ. Another import constituent involved in the CFRP production is the matrix. The matrix of fiberous composites are often from polymeric plastics such as Polyurethane and Polyester. Due to its relatively high modulus and the easiness for in-situ application, epoxy resin is one the most commonly used matrix mateirals for CFRPs used in civil structural retrofit. The epoxy resin covered by this study is produced by BASF, the chemical company. According to the data provided by the manufacture [14], 1 gallon of the epoxy used in this study (mixed) can cover 55 $ft^2$ of carbon fiber fibric. The manufacturing process of epoxy include the synthesis of its two components epichlorohyrin and bisphenol-A, see Figure 7.

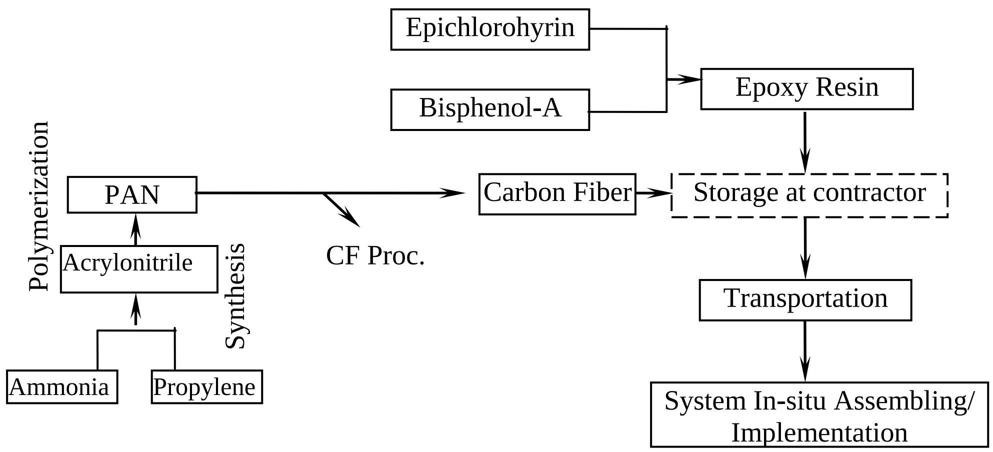


**Figure 7. Elementary Flow of CFRP production (Cradle to Gate)**

*2.3 Transportations*

Since most carbon fibers availuable in the construction market are primarily made in Japan, the crossocean transportation of the carbon fiber has been included in this study as well. Most CFRP systems used for the civil infrastructure retrofit in US are composed of industrial-grade carbon fibers, that are often imported from Japanese manufactures such as TORAY, and US made matrix resins, i.e. the two-component liquid epoxy resin. The data for the transportation phases in this study come from the Ecoinvent Data Base [15]. For example, the GHG emission of operating transoceanic freight ship is 0.00925 kg $CO_2$-eq per [ton-km], and the energy consumption associated to the tranoceanic ship is 0.34 MJ per [ton-km] [16]. After the carbon fiber, usually in rolls of fabric, arrives at the , it will then transported by light trucks to the construction site since the material consumptions for the CFRPs retrofit are often quite low (details will be elaborated in the next section). The data for the light truck operation come from a report released by the Energy Technology Network (ETN) in 2011.

On the other hand, the steel used for the steel jacketting technique is usually manufactured in the local steel mills in the United States. The steel that comes from the ironworks is transported by truck to the local steel fabricators for making the products that could be used for steel jacketting, and then the products are transported to the construction site by trucks.

## 3. Functional Unit Selection

The goal of most structural retrofitting/ strengthening programs is to recover or increase the structure's load bearing capacity, or in some other cases, extend their fatigue life or environmental durability. In this study, we will be focusing on the static load-carrying capacity. Thus, the material usages of the two retrofitting schemes are calculated based on the load capacity of the retrofitted structural members, i.e. bridge girder in this case. The CFRP retrofitting project of a steel reinforced concrete girder was conducted by the author [5], and retrofitting scheme is shown in Figure 8. The design flexural capacity of the each CFRP retrofitted girder is calculated as 142 kNxm. The material consumption for a typical two-lane high way bridge as shown in Figure 3 is calculated as 28.5kg (95m$^2$, 0.165mm thickness) carbon fiber fabric, and 18.3kg (or 18.6L) associate epoxy saturants. In order to achieve the same load-carrying capacity, 4.2mm thick steel (60ksi, or 413MPa) plate will be need for the steel jacketing. The material (steel) consumption for the same two-lane bridge would be 1031 kg. In order to generate projectable results, the **functional unit for this study is selected as ( /standard lane ● 8m-span)**.

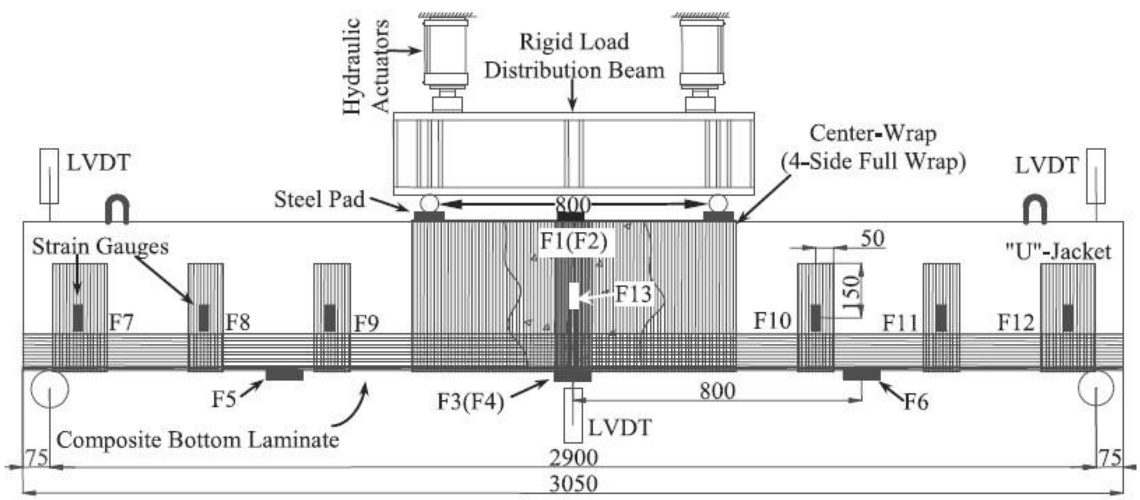


**Figure 8. Retrofit schemes for CFRP retrofitting [5]**

## 4. Impact Assessment

*4.1 Classification*

The impacts are sorted into classes according to the effect they have on environment. The environmental impacts are aggregated within each class to produce an effect measurement. For example, all the green house gases (CO2, N2O, CH4, and Ozone) are calculated into CO2 equivalent (or CO2eq.) based on the their global warming potential. Classification enables the environmental effects of two or more products to be compared. The environmental profiles of the two retrofit techniques are compared for different impact categories and presented in Figure 9. The environmental profiles are caused by the production, transportation, and implementation phases. The maintainance during the use phase is not considered herein due to the lack of research for the CFRP maintainance and durability. For the similar reason, the disposal phase is discarded in this study as well.

Upon the three energy and environmental effects considered by this study, the CFRP retrofit has exhibited better performance. This is primarily due to the much less material consumption (mass wise) in order to achieve the same load carrying capacity for the retrofitted structures. In fact, the energy consumption and GHG emission for manufacruing a unit mass (kg) carbon fiber is significantly higher than steel; however, because its much higher strength as compared to structural steel, only 1/30 of carbon fiber (in terms of mass) as compared to steel would be needed for the same load capacity. The classification step has provided an environmental profile which consists of a fixed set of classification scores on the impact categories taken into account. In this figure the retrofit technique with the highest contribution to a particular effect is indicated with a 100% bar. Interpretation of this figure may be difficult because comparison between impact categories is impossible.

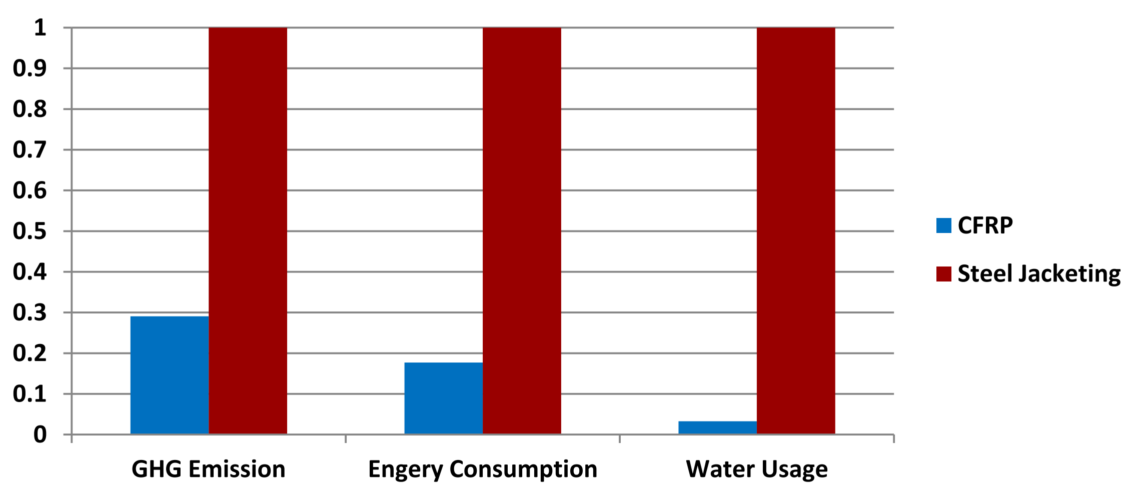


**Figure 9. Characterization for the two retrofit techniques in this study**

*4.2 Evaluation*

Since the data used in this study come from several different sources, the impact profile has NOT been normalized into one single environmental. The Ecoinvent Data Base provides aggregated environmental sores based on different methods for one or two of the environmental indicators considered by this study, however, not all indicators covered by this study were listed (energy consumptions for example). In addition, the weight factor applying to normalize each impact catefory may vary from country to country (or even region to region). For example, the water usage may be a significant indicator in desert regions like Arizona, however, the cases in the areas with abundant water resources may be different. Thus, the restults are reported in its absolute values (per selected units) for each indicator. The uantified conctribution (un-normalized) to each impact category (green house gas emission, energy consumption, and water usage) is presented in Table 1. Because the data were not normalized (or weighted) cross the catagories, the comparison has to be made within each category considered.

| **Carbon Fiber Reinforced Polymer (CFRP) retrofit** | | | | | |
|---|---|---|---|---|---|
| | **Carbon Fiber Manu.** | **Epoxy Manu.** | **Implementation** | **Transportation** | **Total** |
| **GHG Emission ($kg\ CO_2\ eq$)** | 883.5 | 17.591 | 310.43 | 5.5464 | 1217.067 |
| **Energy Consumption (MJ)** | 8151 | 31.842 | 900 | 1034.7 | 10117.542 |
| **Water Usage ($m^3$)** | 68.903 | 8.229 | 0 | 1.033 | 78.166 |
| **Steel Jacketting Retrofit** | | | | | |
| | **Steel Manufacturing** | | **Implementation** | **Transportation** | **Total** |
| **GHG Emission ($kg\ CO_2\ eq$)** | 1030.550 | | 3104.3 | 49.488 | 4184.338 |
| **Energy Consumption (MJ)** | 29280.4 | | 9000 | 18867.3 | 57147.7 |
| **Water Usage ($m^3$)** | 2366.649 | | 0 | 8.8666 | 2375.515 |

**Table 1. The aggragated reults for both CFRP and steel jacketing retrofits**

Figure 10 and Figure 11 present the relative contributions of the processes considered within each of the three impact categories for steel jacketing and CFRP retrofit, respectively. For steel jacketing, the energy consumption and water usage are dominate by the material manufacturing phase, but the implementation phase contributes a significant portion in both GHG emession and transportation. This is mainly due to the high weight of the steel material that requires intensive labor during installation. The impacts of CFRP retrofit, on the other hand, are mainly dominate by the material manufacturing phase. This is attribute to the light-weight property of CFRP and it requires minimal labor during the implementation phase.

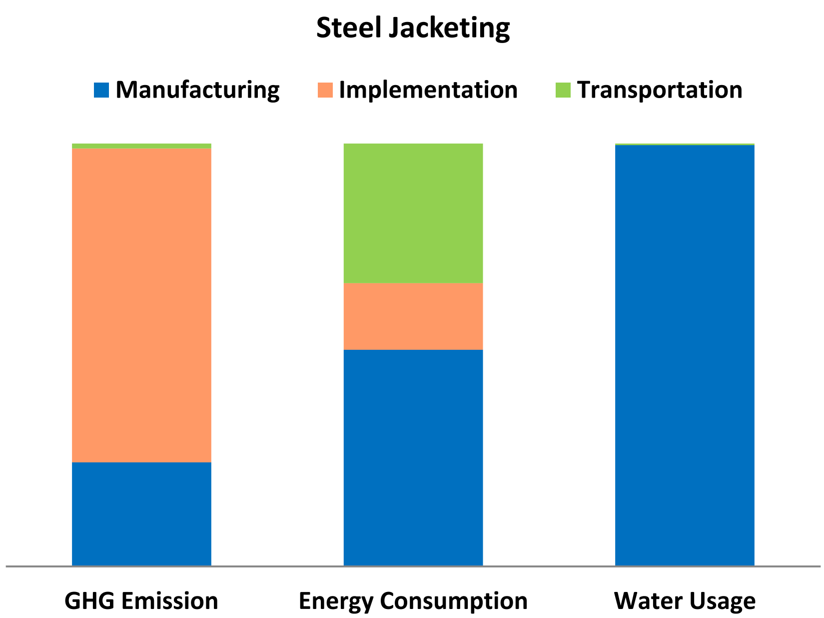


**Figure 10. Contributions of each phase to the total impact - steel jacketing**

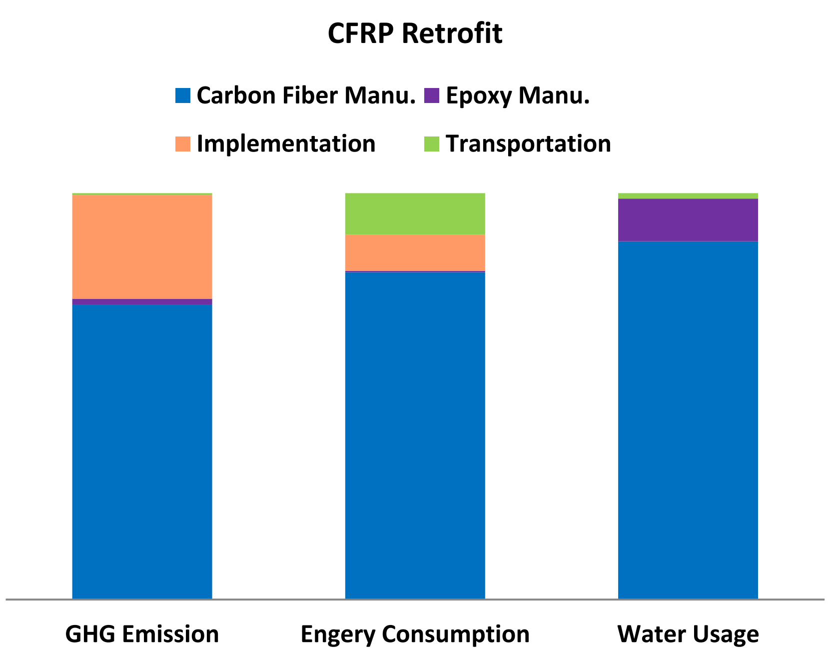


**Figure 11. Contributions of each phase to the total impact - CFRP retrofit**

## 5. Data Quality and Sensitivity

Though high quality data sources are crucial for getting accurate LCA results, however, unfortunately, the data sources that could be used for this study are rare (especially the data regard carbon fiber manufacturing). The following factors may influence the accuracy of the results:

(1) The primary data source used in this study is the Ecoinvent Data Base, where most of the studies were carried out in Europe, however, this study covers the structural retrofit market in the United States. Many factors, such as energy mix, may be very different in Europe than in US.

(2) As for the data used for the carbon fiber manufacturing , data from individual research [12],[17-18] were used. The published data might be sensitive to the time when the researches were carried out, and many of them were for automotive applications.

(3) The construction steel used for steel jacketing is typically recyclable. However, due to the lack of end-of-life research for carbon fiber composites, the disposal phase for both retrofit techniques was not covered in this study.

## 6. An environmentally sound selection for structural retrofit

Through the comparative LCA of two frequently used structural retrofit techniques - steel jacketing and CFRP retrofit, a more environmentally sound solution for structural retrofit would hopefully be determined. The carbon fiber reinforced polymer (CFRP) retrofit technique has shown merits over the conventional steel jacketing in all three impact categories covered by this study. This is primarily attribute to the much less material consumption for CFRP retrofit as compared to steel jacketing, in order to achieve the same load carrying capability for the retrofitted bridge structures. Even though the tranoceanic transportation of carbon fiber has been taken into account in this study, the energy consumption and environmental impacts of CFRP transportation is still much smaller than steel due to it light weight property. The impacts of CFRP retrofit are mainly focused in the material manufacturing phase, which implies that the improvements in the carbon fiber manufacturing technology could potentially further reduce the environmental impacts of CFRP retrofit.

**Appendix I - Example of inventory data used in this study**

Most of the data used in this study come from the Ecoinvent Data Base [15], and patially from individual published research. The inventory data are catagorized and aggregated based on its enviornmental/ or economical impacts. For example, the green house gases ($CO_2$, $N_2O$, and $CH_4$..) are calculated into $CO_2$ equivalent (or $CO_2$eq.) based on the their global warming potential. Table 2 gives an example of the inventory data for the epoxy resin (in liquid form) manufacturing processes.

Table 2. The inventory data associated with the epoxy (liquid) producing process (/kg)

| | Category | Unit | (in kg) |
|---|---|---|---|
| **Green House Gas Emission** | | | |
| Carbon dioxide, biogenic | low population density | kg | 0.0022132 |
| Carbon dioxide, biogenic | high population density | kg | 0.11849 |
| Carbon dioxide, biogenic | unspecified | kg | 0.00061887 |
| Carbon dioxide, fossil | low population density | kg | 0.20227 |
| Carbon dioxide, fossil | lower stratosphere + upper troposphere | kg | 7.5799E-09 |
| Carbon dioxide, fossil | high population density | kg | 0.6036 |
| Carbon dioxide, fossil | unspecified | kg | 0.032655 |
| Carbon dioxide, land transformation | low population density | kg | 0.000021187 |
| Dinitrogen monoxide | low population density | kg | 3.4789E-06 |
| Dinitrogen monoxide | lower stratosphere + upper troposphere | kg | 7.2189E-14 |
| Dinitrogen monoxide | high population density | kg | 8.9234E-06 |
| Dinitrogen monoxide | unspecified | kg | 3.3312E-06 |
| Methane, biogenic | unspecified | kg | 9.1994E-06 |
| Methane, biogenic | low population density | kg | 0.0001344 |
| Methane, biogenic | high population density | kg | 6.8363E-06 |
| Methane, fossil | low population density | kg | 0.0012017 |
| Methane, fossil | lower stratosphere + upper troposphere | kg | 1.2032E-13 |
| Methane, fossil | high population density | kg | 0.000046677 |
| Methane, fossil | unspecified | kg | 1.4621E-06 |
| Ozone | low population density | kg | 1.6657E-11 |
| Ozone | high population density | kg | 8.3886E-08 |
| Ozone | unspecified | kg | 2.5282E-06 |
| | | ... | |
| | | **$CO^2$eq=1.0kg** | |
| **Water Consumption** | | | |
| Water, cooling, unspecified natural origin | in water | m3 | 0.38405 |
| Water, lake | in water | m3 | 1.8225E-06 |
| Water, river | in water | m3 | 0.00012284 |
| Water, salt, ocean | in water | m3 | 0.000097161 |
| Water, salt, sole | in water | m3 | 1.1096E-06 |

| | | | |
|---|---|---|---|
| Water, turbine use, unspecified natural origin | in water | m3 | 0.046212 |
| Water, unspecified natural origin | in water | m3 | 0.019209 |
| Water, well, in ground | in water | m3 | 0.000023175 |

**Energy Consumption***

1.74MJ

**Solid Waste**

Total = 0.043kg

*The energy consumption data is obtained from the study of Vegt and Haije [12].

**Appendix II - Reference List**

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