Design guidelines and life-cycle-cost analysis for the use of recycled plastic lumber (RPL) in structures

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Abstract

Significant process improvements have been made in recent years to enhance the quality and consistency of recycled plastic lumber (RPL). Also, standard methods for testing and determining the performance of RPL are being developed by American Society of Testing and Materials (ASTM) Committee D20. The next step involves acceptance of RPL as a structural material in the marketplace. For this to happen, design guidelines must be established to account for the differences in mechanical properties of RPL as compared with wood. This would enable the use of RPL in construction applications where its corrosion and insect resistance, non-polluting properties and low maintenance aspects would make it a useful material. In a pilot project supported by the State of Ohio, Department of Natural Resources and the U.S. Department of Energy the structural aspects and economics of using RPL for shipping pallets were studied. A procedure to integrate field performance with laboratory evaluation was established. Typical properties of RPL were then used to predict the performance of structural components used in construction using advanced numerical techniques. A life-cycle cost analysis (LCCA) procedure developed by the U.S. Department of Energy (DOE) was adopted to investigate the economics of using RPL pallets versus other options at the DOE site. Plans to' expand this pilot project into a multi-client program to develop standards, generalized design guidelines, product specifications and a database of information for RPL in structural use are also discussed.

Key Words: Recycled Plastic Lumber, Life-cycle cost, design guidelines, shipping pallets

1 Introduction and background

Over the last decade recycled plastic lumber (RPL) has been a very key product in converting waste plastics into useful, high-valued, end-products. The manufacturing methods have been shown to be *both technically feasible and economically viable.* RPL can consume large quantities of mixed, waste plastics; is relatively insensitive to manufacturing variables as compared with other processes used to make plastic products; can tolerate high degrees of impurities and contaminants; can be reinforced with other recyclable wastes such as fiberglass or wood flour; and, requires low capital investment in equipment. RPL, which is currently used primarily in non-load-bearing-applications has not fully realized its potential as a structural material.

Even with limited applications, RPL production stands at about 16 million board-feet (5 million board-meters), or 20,000 tons of waste plastics, per year. More importantly, the growth rate of this industry in the US has been about 40 percent per year in the last few years and there are now over 25 manufacturers. The manufacturing processes and types of RPL have been discussed in detail by Krishnaswamy et al [1] and for brevity will not be included here.

2 Objectives

The objectives of this project were to: (1) determine the technology needs for using RPL in structural applications, (2) define a methodology to establish performance based standards for RPL, (3) validate the methodology through experiments, analysis, and field evaluation, and (4) conduct a life-cycle-cost analysis (LCCA) for assessing the economics of use of RPL in structures. The pilot project used shipping pallets manufactured using extruded RPL in a case study. This paper highlights some of the key findings from this project.

3 Technology Needs for Structural Uses of RPL

There are four major obstacles to be overcome for RPL to be accepted in load bearing applications. The first involves development of standards to test, evaluate and specify the various types of RPL based on its' performance. The second major obstacle is the need for design guidelines that will aid structural engineers to use these standardized properties to compute the stiffness, maximum load carrying capacity, and long term performance of structures. The third barrier is the lack of a database or handbook of mechanical properties and durability data for the various types of RPL. The fourth and final barrier is an accepted LCCA methodology for economic justification for the structural use of RPL.

The Plastic Lumber Trade Association (PLTA) consisting of the manufacturers of RPL together with the American Society of Testing and Materials (ASTM) has formed ASTM Committee D20.20.01 to address the first barrier. This group is charged with developing standard test methods as well as performance based specifications for RPL. Five standards [2-6] been -approved by ASTM and several more have been drafted and are under review.

Outside of this project, however, there has not been a concerted effort to overcome the remaining three barriers. Recently, McLaren [7] has discussed the need for a design methodology and proposed a procedure to develop load-duration-factors for designing with RPL similar to those that exist for traditional materials such as wood or steel.

4 Case study - RPL pallet evaluation

4.1 Laboratory experiments and analysis

In this pilot project for developing a design guideline and establishing a methodology for performance based specification, we chose shipping pallets fabricated from RPL as a candidate product. Since shipping pallets are used extensively by industry and government agencies, developing a performance based specification would be the first step in the creation of a procurement guideline. Such a guideline would significantly expand the available markets for RPL. The U.S. Department of Energy (DOE) needed to investigate the use of RPL pallets at some of their low-level radiation sites and determine whether these were acceptable alternatives to conventional wood and steel pallets. The pallets were essentially used to store and transport 55-gallon drums containing low-level radioactive waste.

The structural requirements of the RPL pallets by DOE at their site in Fernald, Ohio were quite severe. The technical report on this project [8] provides details of these specifications. Several modifications to an existing pallet design were made by Battelle and The Plastic Lumber Company based on past experience with heavy-duty pallets. The engineering drawing for the final design of the RPL pallet used in the field evaluation is shown in Figure 1. Based on past experience, this design was considered to be robust enough for the site requirements.

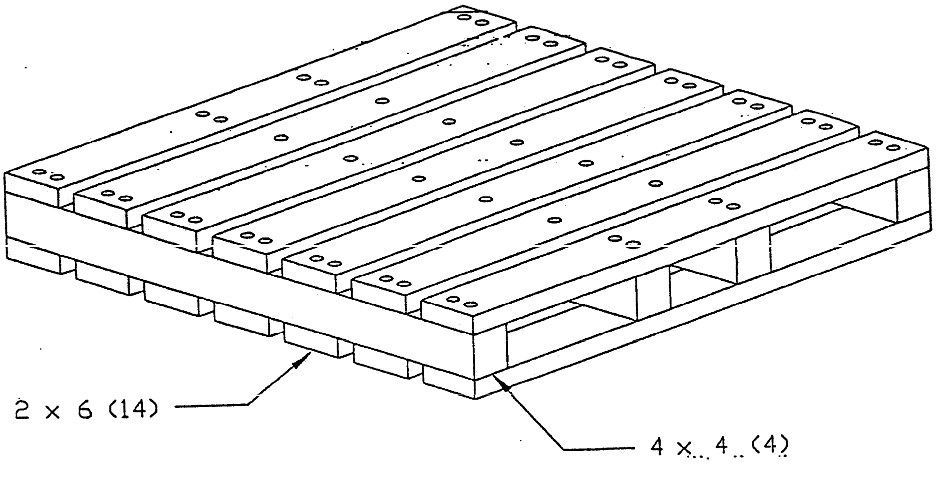

Figure 1. Schematic of the heavy-duty RPL pallet design

However, further full-scale testing of the pallet was conducted to ensure that the load carrying requirements were met. These results are discussed next.

Four RPL pallets were fabricated by PLC as per the above design and the following full-scale tests conducted according to ASTM standards: (1) Stiffness and Flexural Strength tests, (2) Vibration Testing of Pallet Loads, (3) Lateral Stability and Diagonal Rigidity tests due to drops, (4) Impact Test of Leading Edge, Blocks and Posts, and 5) Compression Test of Pallet with a simulated four, 55-gallon drum loading configuration. Details of these test procedures and results are provided [8]. Figure 2 shows the load-deflection curve for the pallet under compression load configuration using four 55-gallon drums. As seen, the maximum load carrying capacity in this test configuration is 20,355 pounds, which exceeded the requirement of 19,200 pounds by DOE-Fernald. The pallets also passed the vibration, drop and impact tests.

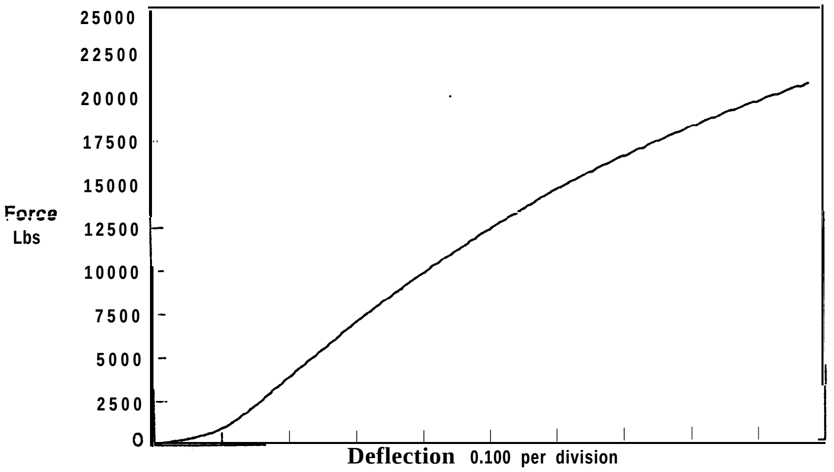

Figure 2. Load-deflection curve from full-scale test on RPL pallet under 4x55-gallon drum

An attempt was made to simulate the full-scale behavior of the pallets using the RPL material properties and Finite Element Analysis (FEA). The mechanical properties required of RPL for the computer simulation included flexural properties for the lumber (2”x6”) and the compression properties of the stringers (4”x4”). A typical flexural stress-strain curve conducted using ASTM D 6109 is shown in Figures 3. These data were used in the finite element simulation.

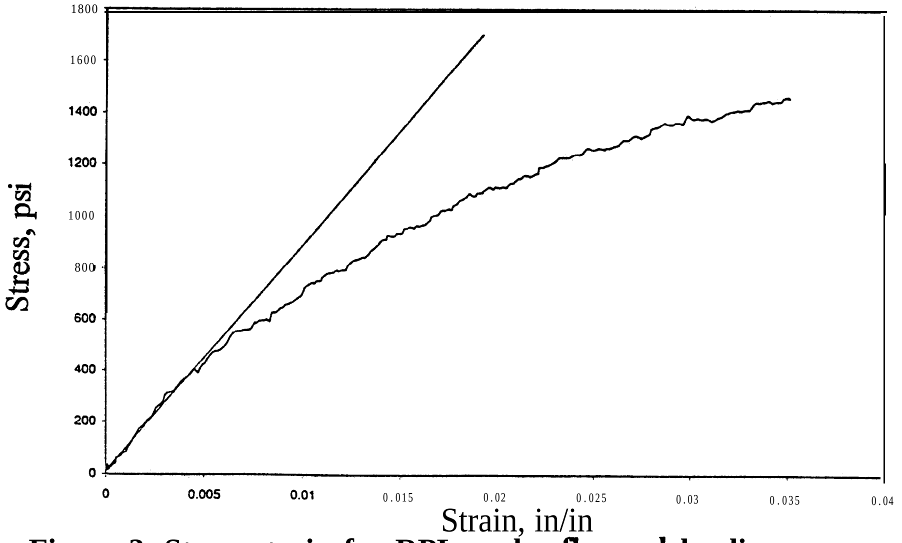

Figure 3. Stress-strain for RPL under flexural loading

. A three-dimensional FEA model of one-quarter of the pallet was developed to simulate the full-scale test conducted. The results of the computer simulation indicate that the maximum loads were over-predicted by a significant margin. The level of discrepancy is not unexpected as the RPL is assumed to be homogenous and isotropic in the simulation while in reality it has a skin and foam core that is not homogenous and therefore anisotropic with regard to its stiffness and strength. Thus the original assumption is not valid and a better procedure to analytically evaluate RPL structures is currently being developed. Figure 4 shows that the deformed pallet shape qualitatively matches the experimental observations.

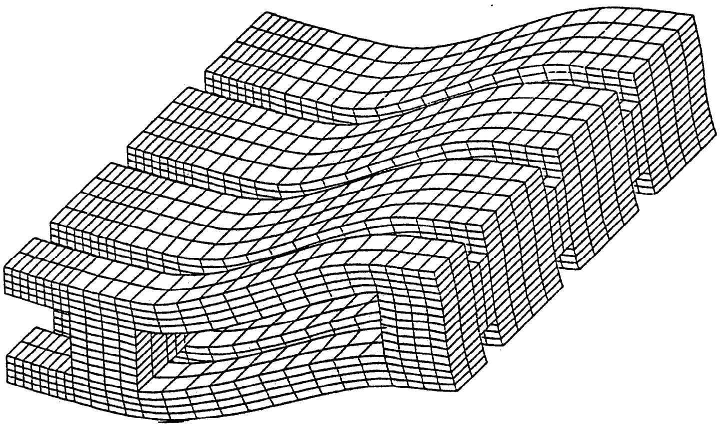

Figure 4. Finite element simulation of RPL pallet showing deformed shape

4.2 Field evaluation of RPL pallets

Six pallets fabricated to the design specifications were sent to DOE-Fernald for field evaluation. These were distributed among three locations within the site as follows: Location 1 – Production (5 pallets), Location 2 – Training (2 pallets), and Location 3 - Northstar (1 pallet). The evaluation conditions and findings are summarized below.

Location 1- Production: Three of the pallets were used at this production location where the pallets would be exposed to radiation. The three pallets were in a racked 'static load' configuration with four 55-gallon drums on each pallet. The material in the drums was Mag Flouride and the pallets were placed outdoors on a concrete floor. The total load on the bottom pallet was 9006 pounds (4094 kg.) and was sustained for five weeks.

Location 2 - Training: The training facility was supplied with two pallets and were subjected+ to 'dynamic loading', that is, they were used to move drums from one place on the location to another using fork trucks. The facility used to train operators of forklifts subjected the pallet to severe use with constant dragging and pushing of the pallets and the materials on it. Drums weighing about 4000 lbs were stacked and unstacked on these pallets routinely.

Location 3 - Northstar: The last pallet in the evaluation was used at this location for handling and moving 'dynamic' loads other than drums. The pallet was used to transport office equipment, desks chairs, etc. using fork trucks. The intent at this location was to study the pallet behavior under nonstandard loading configurations.

As indicated in the field performance reports [8], the pallets performed very satisfactorily at all three locations under a variety of loading configurations. There was no evidence of damage or cracks as a result of the sustained load. Apart from normal wear of the loading surface the pallet remained intact and no excessive deformation was noted at these usage levels. At the end of this period the top most pallet in Location 1 was removed from service and checked for radioactive contamination. No contamination was evident and the pallets were ‘free-released’.

5 Life cycle cost analysis methodology

DOE-Fernald along with the Oak Ridge National Laboratories (ORNL) has developed a formal procedure for the life-cycle analysis of products and processes. This procedure provides a formal framework for evaluating the viability and economic feasibility of various options for a given process. This procedure detailed in [9 and 10] accounts for both tangible and intangible factors that affect various options for recycling and disposal at DOE sites. Embedded in these procedures is the LCCA of various product options for a given application. This procedure was followed in conducting the LCCA for RPL pallets versus other options.

The basic definition for ‘life-cycle cost’ in the DOE [9, 10] methodology is as follows: life cycle cost include the direct, indirect, recurring, nonrecurring and other related costs incurred or estimated to be incurred in the design, development production, operation, maintenance and support of an asset throughout its anticipated useful life span and through final disposal. Revenues such as user fees and salvage receipts should be included as an offset to the cost. The steps in the LCCA were as follows:

1. Identify the alternatives: In the case of pallets at DOE-Femald the alternatives available were: wooden pallets, galvanized steel pallets, and, RPL pallets.
2. Identify the life-cycle duration for each alternative: Since DOE-Femald is on a lo-year shutdown plan, the time duration for pallet needs for this study is 10 years. The estimated value of the design life for the alternatives were as follows [8]:

Pallet Type	Design Life, years
Wood	2
Steel	10
RPL	5

3. Identify the cost categories for each pallet type: Various categories of costs for each alternative are as follows:
    - Acquisition (Initial) Cost: The cost of purchasing new pallets are:
      Wood - $20
      Steel - $160
      RPL - $275
    - Maintenance and Repair: Based on experience, some assumptions need to be made regarding frequency of repair and the cost of each repair for the various alternatives. It is assumed that the wooden pallets with a design life of 2 years are not repaired and are disposed off. The metal pallets being robust may not need any repairs during the lo-year life. Some of the boards on the RPL pallets may need to be replaced once during its design life of 5 years. The cost associated with this repair is accounted for in the LCC of the RPL pallet.
    - Disposal or Recycling Cost at end-of-life: At the end of their useful life since they are ‘suspect-contaminated’ the wooden and metal pallet, had to be disposed off through the appropriate procedure for contaminated materials. The cost of these options was included

in the analysis. Since the RPL pallets are not contaminated by radiation, they can be disassembled and recycled or sold as is for reuse under free-release conditions.

4. Identify costs in each year: Depending on the design life, maintenance required or disposal alternative involved the costs during each of the 10 years is identified.
5. Identify discount rate: For a 1 O-year project the real discount rate, R, is 3.5 percent as specified by the Office of Management and Budget [11].
6. Calculate present worth using discount rate: The total cost for each year is reduced to a net present value (NPV) using the formula

$$\mathbf{NPV = (Cost\ for\ Year\ Y)/(1+R)^{Y}}$$

where R is the discount rate and Y is the year under consideration. The total NPV for all 10 years then provides a life cycle cost for the given alternative.

The NPV value for the three options for the lo-year period were as follows:

Pallet Type	LCC at NPV
Wooden	$815
Galvanized Steel	$517
RPL	**$587**

As seen, even though the initial cost of RPL pallets was considerably higher than the wooden pallets (Item 3 above), over the duration of lo-years the RPL pallets have a lower LCC. The RPL pallets are directly competitive with the Galvanized Steel pallets as the LCC for the two options are within 25 percent (the limits set by DOE methodology) of each other.

The DOE methodology [9,10] calls for evaluating the various alternatives using a Decision Matrix which account for both LCC as well as other intangible factors such as local public acceptance, impact on environment, institutional preference and worker safety impact. When all these intangible parameters were taken into account the RPL pallet did become a preferred option from the viewpoint of a life-cycle economic analysis.

6 Conclusions to date

The major conclusions regarding the development of design guidelines for structural uses of RPL include the following:

1. A combination of laboratory, full-scale and analytical predictions are needed to establish design guidelines for RPL in structures,
2. The ASTM standards provide necessary but not sufficient information for developing performance based specifications,
3. Design criteria must account for the unique type of material behavior exhibited by RPL in order to take advantage of all its other features and benefits.
4. A life-cycle cost analysis is usually needed to evaluate the economic feasibility of optional products to justify the use of RPL in structures.

8 Future work

Future efforts to expand the case study and pilot project described above involves a multi-client partnership between, state governments, federal agencies and the private sector. This partnership, is being coordinated by Battelle and the Plastic Lumber Trade Association and is addressing methods to overcome the barriers to RPL in the structural marketplace. This is a three-year, three-phase study that focuses on major potential applications for RPL, namely outdoor residential decks, marine boardwalks and other structures, and material handling items such as pallets. For each of these applications optimized design guidelines, durability information, and a database of appropriate material properties is being developed. The results of this study will be presented at future meetings.

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