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Effect of Temperature on Static and Impact Properties of New Softwood Pallets

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Abstract The first part of this study verifies that static compressive strength of new wooden pallets decreases as temperature increases. The drop of compressive strength is at a small rate of 0.61 psi per 1°F of temperature increase within the temperature range of 80°F to 160°F. This is consistent with the current timber structural design practice. The strength reduction is small and has little effect on pallet static compression performance. The second part of this study investigates impact acceleration from free-fall drop tests performed at temperatures ranging from 80°F to 160°F. As temperature rises, specimens become weaker thus they absorb more impact energy, which results in lower impact acceleration. The drop of impact acceleration is also at a small rate of 0.034g per 1°F of temperature increase. When temperature rises from normal temperature of around 80°F to a high temperature of 160°F, the impact acceleration reduces about 2.72g. This rise results in less potential damages on products on the pallet. The third part of this study looks at the impact acceleration due to horizontal impact due to a forklift at a lower range of temperature of 33°F to 72°F. The drop of impact acceleration is at a faster rate of 0.674g per 1°F of temperature increase. When temperature drops from 59°F to 48°F, the impact acceleration increases about 7.41g. This increases the damage potential of products on pallets.

Keywords *High Temperature; Low Temperature; Compressive Strength; Impact Acceleration; Softwood Pallets; Free-Fall Drop Test; Forklift Impact Simulation*

1. Introduction

Pallets are handled under different temperature environments. On a hot summer day in Arizona, a pallet in a tractor-trailer could be subjected to over 150 °F temperature. On the other hand, during a cold night in Michigan a pallet left outdoor could be under freezing temperature. It has been well established in timber structural design, such as for buildings, that a timber member under high temperature for a substantial period of time becomes weaker under static loading. The National Design Standard [1] reduces the allowable stress by a factor of C_t when a timber member is in such a situation. In this research, wood specimens were prepared from new softwood pallets. Static compression tests were performed to validate the timber design practice above. Drop test, a simulation of vertical dropping of a pallet by a forklift, was performed to gain insight of how high temperature affects pallet impact property. Finally, incline impact test, a simulation of horizontal impact on a pallet by a forklift, was performed at lower temperature to see the effect of low temperature on pallet impact property. A normal temperature used in the study is around 70°F, which is the typical temperature in the CBU certified packaging laboratory and is comparable to the normal controlled condition used by test procedures, such as ISTA Procedure 3A [2], set by the International Safe Transit Association, i.e., 73°F and 50%RH.

2. Materials and Methods

2.1. Temperature Range & Monitoring

The first phase of this study is the determination of the range of temperature to be used. The normal temperature used for the high temperature study part was 80°F, representing approximate lab temperature during the summer when the study was conducted. This is slightly higher than the ISTA normal temperature of 73°F. The normal temperature used for the low temperature study part was 73°F, representing approximate lab temperature during the fall when this part of study was conducted.

The upper limit for the high temperature study was selected as 160°F based on several considerations:

- The heat treatment process that is used to eliminate pests from pallets requires wood packaging materials to be heated with a minimum temperature of 132.8°F for a minimum duration of 30 continuous minutes to heat the wood thoroughly [3].
- On a hot summer day in Memphis, TN, with an exterior temperature of 92°F, the interior temperature of an enclosed outdoor storage, measured by an infrared thermometer gun, was 155°F. The interior of a tractor-trailer would be around the same figure.
- The following model, Eq. 1, was developed from heat transfer principles [4] for a parked tractor trailer:

$$T_i - T_\infty = \left(\frac{q_s \alpha}{1.91/W^{1/4} + 2.84H^{3/4}\left(\frac{1}{W}+\frac{1}{L}\right)} \right)^{0.8} \qquad \text{………. Eq. 1}$$

Where T_i = interior temperature of tractor trailer (°C), T_∞ = exterior temperature (°C), q_s = sun load (1000 W/m^2), α = absorptivity of solar radiation, L = length of tractor trailer (m), H = height (m), and W = width (m). Figure 1 shows the relationship between interior and exterior temperatures, which were converted from °C to °F, at different absorptivity.

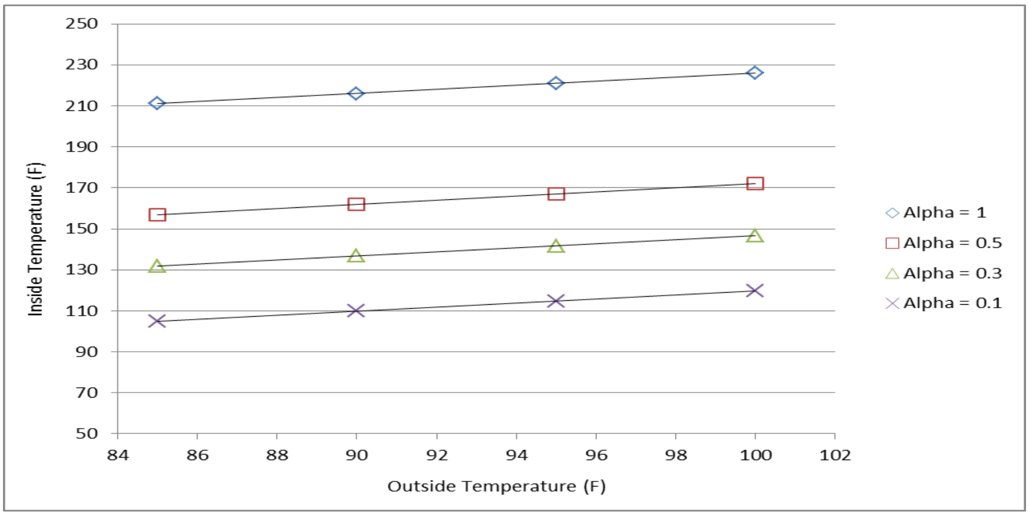

Figure 1: *Interior and Exterior Temperatures of a Parked Tractor-Trailer*

This equation demonstrates that the truck container would absorb all the sun heat when Alpha = 1 and reflect most of the sun’s heat when Alpha = 0.1. A more realistic absorptivity of solar radiation is around 0.5, thus an interior temperature of around 150°F to 170°F would be reasonable.

The lower limit of the low temperature study was 33°F, just slightly above the freezing point to avoid the change in wood’s internal structure due to freezing.

For the high temperature study, samples of softwood pallet stringers were placed over night in a temperature/humidity chamber which was set at 180°F temperature and 40% relative humidity as shown in the left photo of Figure 2. Each sample was then placed at room temperature with thermocouples placed at mid-depth, quarter-depth, and on the surface as shown in the middle photo of Figure 2. The end of each thermocouple wire exiting from each specimen was also sealed to prevent heat loss through the hole made for thermocouple insertion. However, these seals are not shown in the figure. A PC-based data acquisition system was used to record and plot temperature values from thermocouples at a 2-minute time interval (with the first reading at 160°F) until the temperatures dropped to room temperature as shown in the right photo of Figure 2. Only mid-depth temperature values were used to represent the temperature state of a specimen at a given time for simplicity. Figure 3 shows cool-down curves for three softwood stringers. An average temperature equation was used in estimating temperature of a specimen during compression test and impact test.

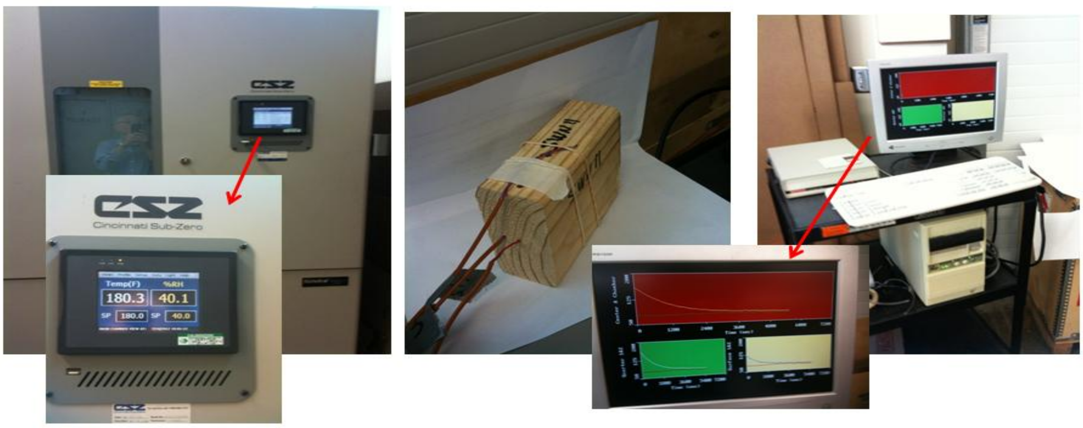

Figure 2: *Temperature Monitoring for High Temperature Study*

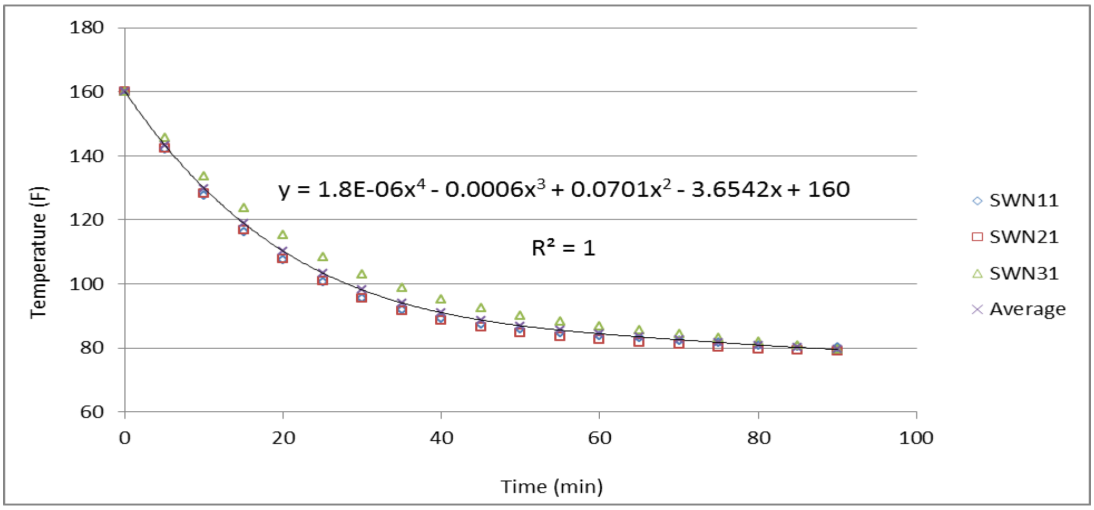

Figure 3: *Cool-down Curve for High Temperature Study*

For the low temperature study, a specimen was placed in a chamber at 33°F with thermocouples inserted into the specimen at mid-depth, quarter-depth, and on the surface to monitor the temerature. Once the temperature at mid-depth of specimen reached 33°F, the specimen was allowed to warm up outside the chamber. A temperature profile was developed in Figure 4.

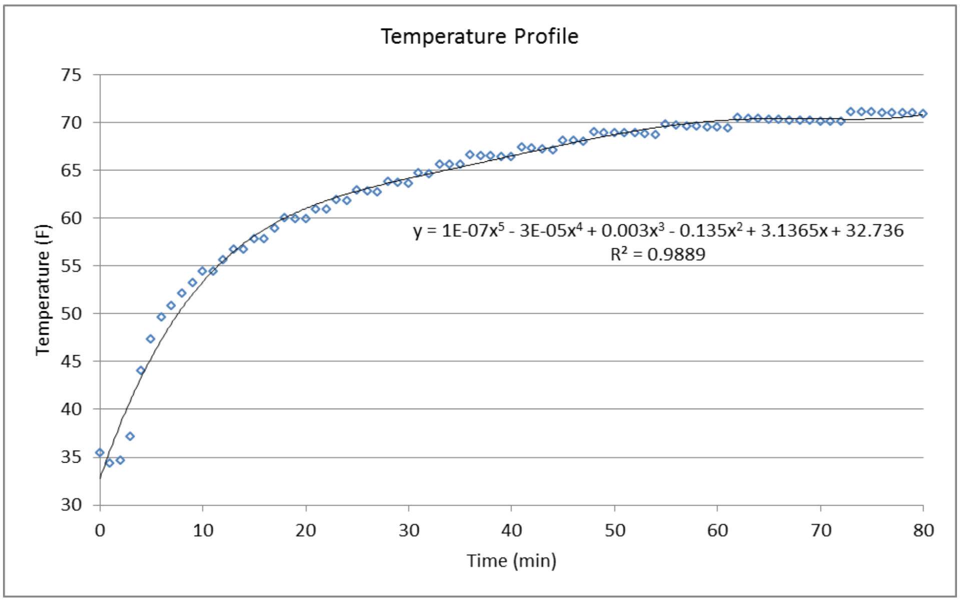

Figure 4: *Warm-up Curve for Low Temperature Study*

2.2. Compression Test

Stringers are the main part of a pallet that resists vertical load. Thus, stringer specimens were used in static compression test in this study. Fourteen specimens were placed overnight in an altitude chamber (photo on the left in Figure 5) with the temperature set to 82.2°C (180°F). The time a specimen was removed from the chamber to the first compression test is about the same as the time when it was removed from the chamber to the time the thermocouples made their first readings of the temperature as mentioned earlier. Knowing the time from the compression of the first specimen, the temperature of a subsequent specimen was determined by the average cooling equation shown in Figure 3. Each specimen was compressed in a compression machine (photo on the right in Figure 5). Compressive stress was calculated for each specimen using the following equation:

$$Compressive\ Stress = \frac{Maximum\ Load}{Area} \qquad \text{……….. Eq. 2}$$

Figure 5: *Equipment Used in Static Compression Test*

2.3. Free-Fall Drop Test

Due to the limited size of the temperature/humidity chamber, two smaller specimens (as shown in the lower left photo in Figure 6) were made to replicate a real pallet. Each specimen consists of three stringers taken from three different pallets. A data logger (also known as "saver" or "transportation recorder") was placed on layers of 5/16" bubble wrap sheets and housed in a single-wall corrugated box (as shown in the upper left photo in Figure 6). Four to eight layers of bubble wrap were used to see what the effect of cushion has on the impact acceleration. The instrument's box was then secured to each specimen with a plumber strap. Drop tests were then performed at a 12-inch drop height (as shown in the right photo in Figure 6).

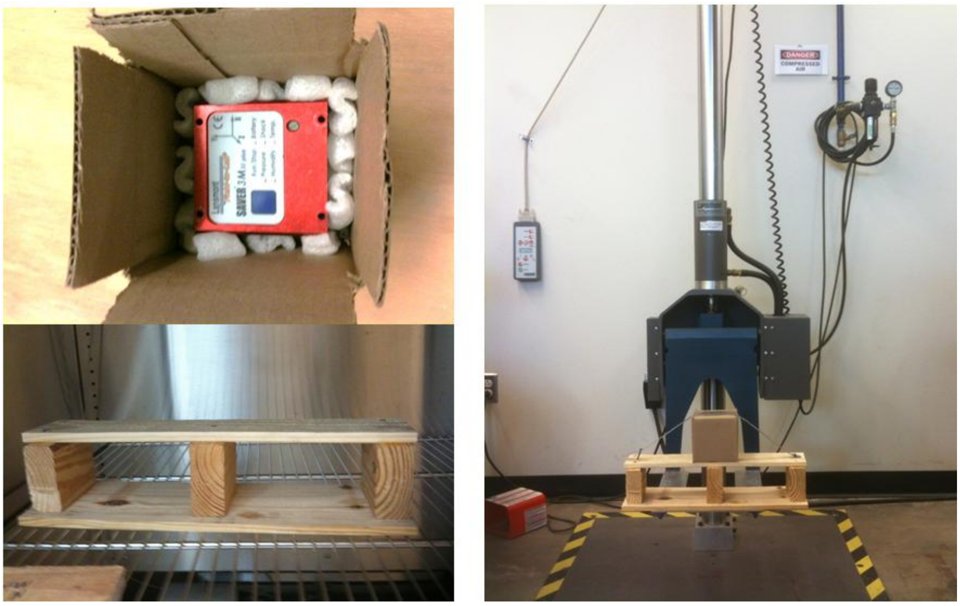

Figure 6: *Drop Test of Pallet Specimens*

2.4. Incline Impact Test

An incline impact test was used to simulate horizontal impact from a forklift at low temperatures. The setup was similar to that of a previous study [5], as shown in Figure 7. The specimen was impacted at about 5-minute intervals for about one hour. The shock recorder had the time stamped for impact acceleration recorded. Knowing the time of impact from the time the specimen was taken out of the *temperature* chamber led to the determination of temperature at impact as produced from the temperature profile shown in Figure 4.

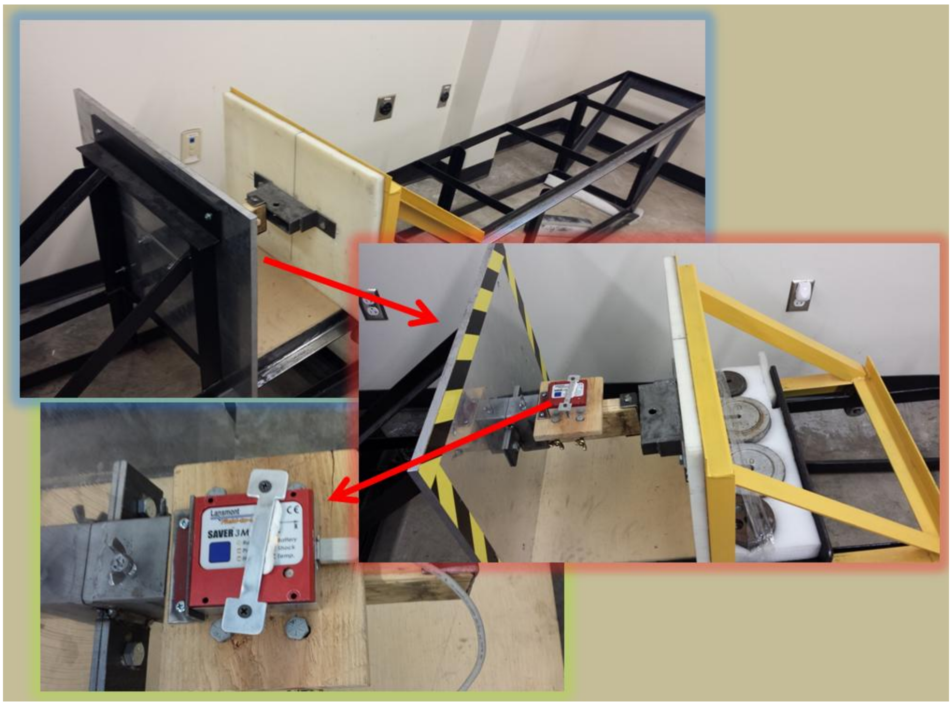

Figure 7: *Incline Impact Test Setup*

3. Results and Discussion

3.1. Compression Test

Compressive stress, calculated from Eq. 2, was plotted against estimated specimen temperature as shown in Figure 8. The trend of the curve indicates that the pallet stringer is weaker at higher temperature, thus indicating lower compressive stress. This validates the current practice in timber design. Data points are not quite consistent since each specimen is different. A specimen is crushed to failure; thus, a new specimen must be used where temperatures may fluctuate. It is a well-known fact that wood properties vary significantly. In addition, the direction of wood grains affects the compressive strength as pointed out in a previous article [5].

3.2. Free-Fall Drop Test

Results from the drop test were plotted in Figure 9. The black equations are from specimen No. 1 while the red equations are from specimen No. 2. Specimen No. 1 was made from new softwood pallets while specimen No. 2 was from heat treated softwood pallets. Since both specimens were heated to 180°F overnight, which was greater than the temperature and duration requirements specified in ISPM 15 [3], both specimens are essentially heat treated. In Figure 9, S_{ij} means the i^{th}

specimen with j layers of bubble wrap; e.g., S24 means specimen No. 2 with four layers of 5/16" bubble wrap.

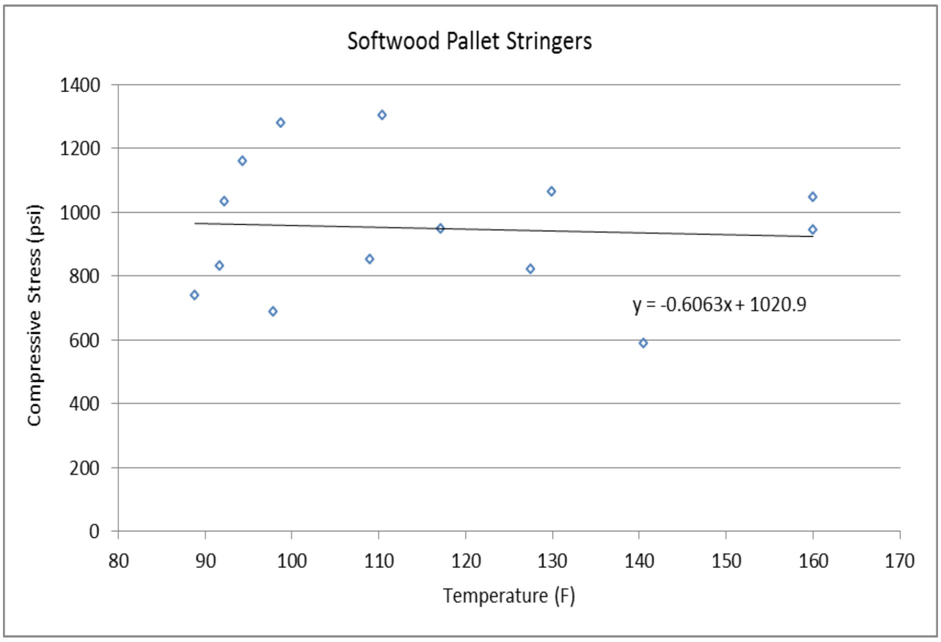

Figure 8: *Compressive Strength versus Temperature Graph*

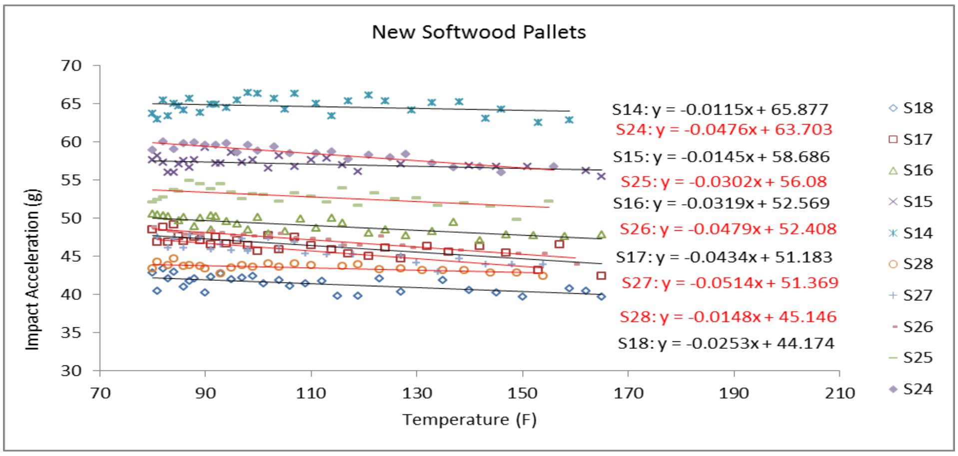

Figure 9: *Drop Test Results*

The following observations can be made from Figure 9:

- All lines shown have negative slopes. Thus, the temperature affects the impact property the same way it does for static compressive loading. As temperature rises, the wood becomes weaker, thus it deforms more. With more deformation, the pallet absorbs more impact energy, thus results in lower impact acceleration.
- The five black equations for specimen No. 1, i.e., S14, S15, S16, S17, and S18, are relatively parallel.
- The four red equations for specimen No. 2, i.e., S24, S25, S26, and S27, are also relatively parallel. S28 line seems to be skewed from the group.

- The average slope for specimen No. 1 and No. 2 are -0.025g/°F and -0.038 g/°F, respectively. The average slope of all ten specimens is -0.034g/°F with a range from -0.051g/°F to -0.012g/°F.

3.3. Incline Impact Test

Impact accelerations were plotted against temperature as shown in Figure 10. The acceleration became constant between 58°F to 72°F. Thus, only data between 48°F to 58°F was plotted in Figure 11.

The following observations can be made from Figure 11:

- The trend follows the same pattern as the static compression test and vertical drop test results. As temperature increases, the wood becomes weaker resulting in more deformation which allows more energy to be absorbed.
- On the opposite direction as temperature drops from normal temperature to near freezing, the wood becomes harder with less deformation, thus higher impact acceleration. This has potential in creating more damage to contents on the pallet.
- The rate of change as temperature increases is -0.674g/°F. Thus, dropping temperature from a temperature of 59°F to 48°F results in an increase of 7.41g of impact acceleration.

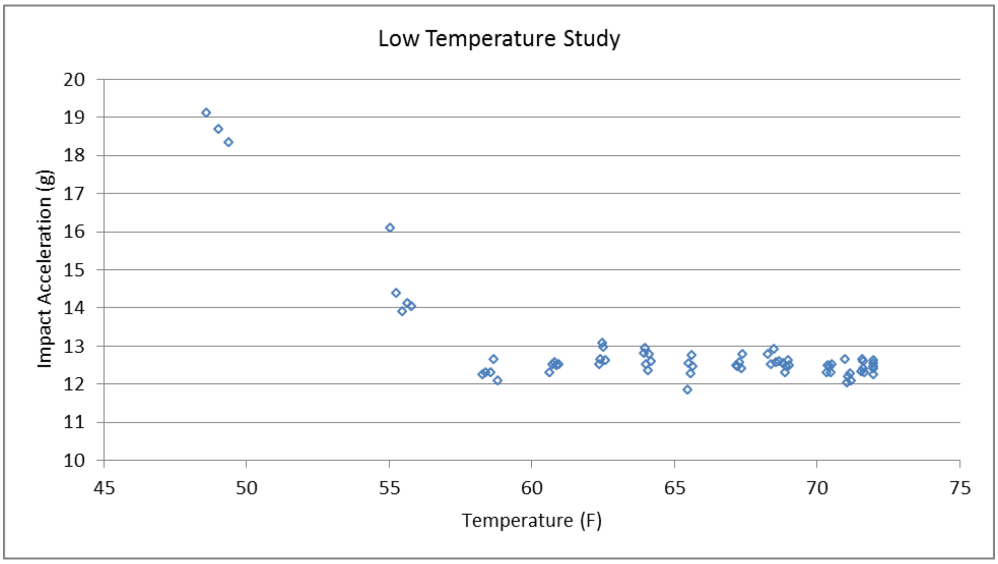

Figure 10: *Impact Acceleration vs Temperature (48°F to 72°F)*

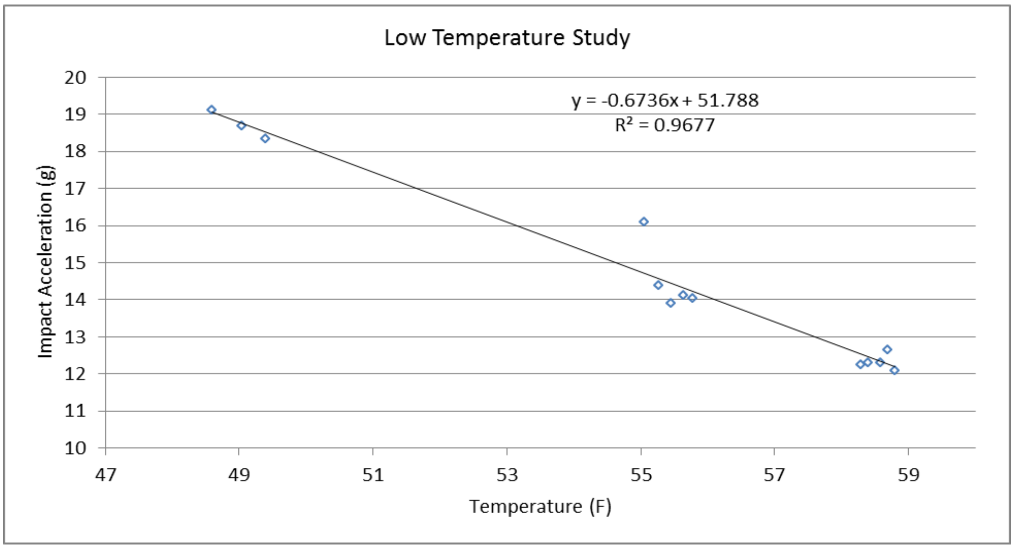

Figure 11: *Impact Acceleration vs Temperature (48°F to 59°F)*

3.4. Effect of Temperature Range

Range of temperature used in developing a temperature profile has an effect on the prediction of temperature. As an example, Figure 12 shows three cool-down temperature profiles starting from different temperatures and merging to the same room temperature. For a given test time, t_1 , three different temperatures, T_1 , T_2 , and T_3 , can be predicted. However, in this study the same temperature range was used in the temperature profile development and an actual test. Thus, temperature prediction was accurate.

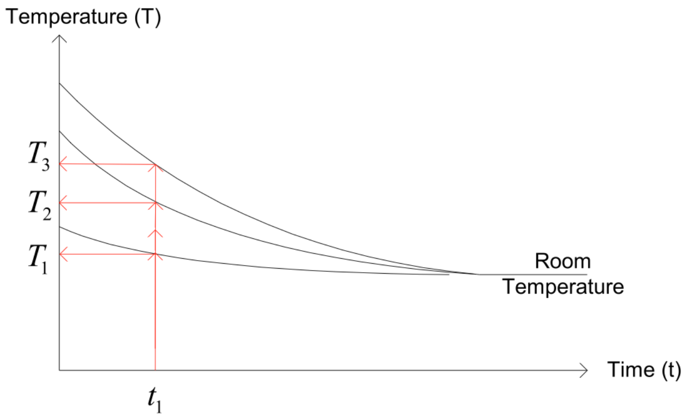

Figure 12: *Effect of Temperature Range Used in Developing Temperature Profile*

4. Conclusions

The following conclusions can be made from this study:

- As the temperature rises, wooden pallets become weaker in compression resistance. However, the drop is not significant. Within the 80°F to 160°F range used in this study, the compressive strength drops from 972 psi at 80°F to 923 psi at 160°F, which is about a 5% drop in strength.

- As the temperature rises, wooden pallets absorb more impact energy therefore the impact acceleration felt at the top of pallet is reduced. Thus, it is better off in terms of damage potential from impact for a pallet to be under high temperature, such as 160°F, than at a more normal temperature, such as 80°F.
- As temperature drops, wooden pallets absorb less impact energy. This increases the potential damage to products on pallets.
- Since wood properties vary significantly from one piece to another, the rates of change calculated in this article could vary somewhat. However, the trends should remain consistent.

Acknowledgement

The static compression test and vertical drop test of this article were previously published in the Proceedings of the 2012 HPC Fall Meeting (November 2012) in a paper entitled "*Effect of High Temperature to Compressive Strength and Impact Acceleration of New Softwood Pallets*". Use with permission from Christian Brothers University.

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