Structural Performance of thinned oak containers

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Abstract

Traditional containers such as barrels, used in the transportation and storage of food and liquid, have been constructed from timber for thousands of years. The design of the container has evolved over time and the original design specifications have not altered until recent times. Storage of high strength spirit such as whisky has lead to the containers being used for flavour purposes as well as storage. Consequently the inner surface of the barrel is becoming thinner, raising concerns regarding the structural integrity of the barrel in modern warehousing. Warehousing of timber barrels in modern industry utilises palletising techniques made possible by advances in transportation technology, such as forklift trucks. In-turn, this has placed a modern day requirement for the barrel to withstand additional and non-traditional loading within a palletised system. Consequently, under load, the curved timber of the barrel has a stress concentration generated about the mid-line, leading to concerns regarding structural integrity. The six supporting hoops of the barrel are traditionally used for maintaining shape and retention performance. However, under the new loading conditions of palletisation, they absorb the stress as the barrel displaces, reducing the stress concentration about the mid-line, up to the ultimate loading of the timber. The effect of hoop arrangements on structural integrity during palletised loading has been investigated using FEM to establish the optimal orientation with the aim of increasing the overall stiffness of the structure. Experimental validation of the optimal hoop locations about the cask established in the FEM environment has been conducted. The experimental investigation compares modified and un-modified barrels with respect to their limiting stress conditions, comparative stiffness' and curvature displacement magnitudes.

1 Introduction

Traditional oak containers, such as barrels, have been used for over 2000 years in the storage and transportation of food, liquid, meats and even gun-powder (Kilby 1989). Over the past 200 years, the oak barrel has been adopted by the alcoholic drinks industry, largely Scotch and American Bourbon, due to the flavour impact the timber has on the liquid. The flavour is derived from the firing of the internal surface of the barrel whereby the natural components of the timber (i.e. lignin, cellulose, hemi-cellulose etc.) are degraded to produce flavour compounds such as vanillin and syringealdehyde. These flavour components add to the new make alcohol during the maturation of the liquid as

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spirit interacts with the timber. The flavours of the barrel will eventually become exhausted after a number of consecutive fillings and therefore be returned to the cooperage for “rejuvenation”.

The rejuvenation process involves a flailing and firing process whereby the internal surface of the barrel is scrapped to remove old/ exhausted timber to allow for a re-heating of new timber to regenerate flavour compounds, thereby extending the working life of the barrel.

Evolution of warehousing and transport technology, such as forklifts, and consequently barrels are stored vertically in palletised warehousing instead of the traditional horizontal storage. With modern techniques of flailing now able to remove 2mm per rejuvenation, concerns have been raised as to the structural integrity of the barrel structure with the additional loading. These concerns are amplified with respect to ‘thinned’ barrels becoming more common, especially within the wine and spirits industries.

2 Methodology

The structural optimisation of the barrel design was based on firstly quantifying the current “thinned” barrel performance under load and quantification of mechanical timber properties of the American oak material under investigation. Following the experimental analysis, Finite Element Analysis techniques were used to optimise the orientation of supporting hoops to provide the maximum possible strength under load.

2.1 Experimental

Test barrels were constructed from “thinned” staves at approximately 12mm, 14mm, 16 mm and 18 mm. Barrels of regular stave thickness (approximately 26mm) were also tested. The barrels were filled with water, kept for a minimum of 2 weeks and emptied before filling to ensure similar moisture content to that of barrels in warehousing.

The assessment of structural performance of thinned barrels was conducted to determine the load-deformation characteristics before optimisation of hoop orientation. Displacement transducers were placed around the centreline of the barrel bilge (the widest circumference of the barrel) to monitor deformation of global circumference. Displacement in stave bilge around the barrel is due to the stress concentration at the weakest component of the timber (transverse grain of the stave under combined bending and tensile stresses) and therefore requires optimisation. Figure 1 shows the schematic of displacement transducer locations (a total of 8) about the barrel bilge for monitoring stave displacement.

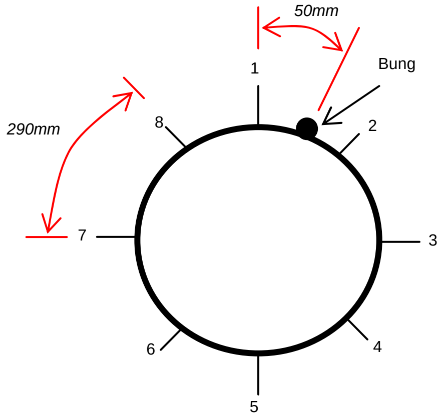

Figure 1: Schematic on displacement transducers about the barrel bilge

The barrel was loaded to 10kN at a ram rate of 2mm per minute together with a data sampling frequency of 10Hz. The barrel was hardened for four cycles before data was collected on the fifth. Three barrels at each stave thickness were analysed in this investigation.

2.2 Oak material properties

Timber properties vary hugely depending upon origin of growth and operating conditions. Consequently, mechanical material properties associated with oak barrels required quantification. Employing EN 408 standards (EN 408:2003), MOE values were established for the oak material in compression, parallel and perpendicular to the grain, and also tensions parallel to the grain, as these were the only orientations available for testing due to the timber available from a pre-constructed barrel. Due to the nature of the experimental set-up, the staves were all measured at 12% MC to allow for the attachment of strain gauges to the porous material.

2.3 Finite Element Analysis (FEA)

For the optimisation of the barrel hoop locations for increases to the overall stiffness of the structure, a finite element analysis was conducted. Using the orthotropic oak material properties quantified in 2.1.1 a CAD model was developed and analysed in the FEA environment. Oak/Oak (0.4) and Oak/Steel (0.5) frictional coefficients were used together with a tetrahedral mesh of over 300,000 elements and a specific hoop sizing control of 25mm. In a five-step analysis, a realistic load of 10kN was applied to the top edge of the barrel (staves and end hoop) in the vertical orientation and a fixed support to the lower edges. This would allow for validation of the model using the current barrel hoop locations before re-locating, establishing the optimal stiffness achievable.

For comparable measurements, probes were assigned to six equidistant staves about the bilge curve at the barrel centreline to monitor horizontal displacement (Figure 2), similar to those studied in the structural analysis. In addition to the FEA probes about the bilge circumference, probes were placed vertically on the selected staves at 0.25 and 0.75 of the overall height, (Figure 2) monitoring horizontal displacement and therefore quantify the overall displacement of the staves.

Following, validation of the FEA model, the bilge and quarter hoops were relocated and the horizontal displacement of the staves was analysed and compared. Placement of the hoops was calculated by taking the centreline of the barrel and placing the bilge hoop at 75mm above and below. Placing the hoops at the exact centre line is not possible due to the location of the bung hole, used for filling and disgorging the barrel. The quarter hoop was then relocated about the centreline using various ratios of the bilge hoop distance from the centreline (i.e. 1:1.5 ratio gives bilge hoop location: 75mm from the centreline with quarter hoop location: 187.5mm. 1:2 ratio gives bilge hoop location 75mm with quarter hoop location: 225mm). In addition to the 75mm bilge hoop placement analysis, a 100mm analysis was also conducted. This was to assess the influence of bilge hoop locations along with the quarter hoop, to ensure that the barrel was optimised for all components.

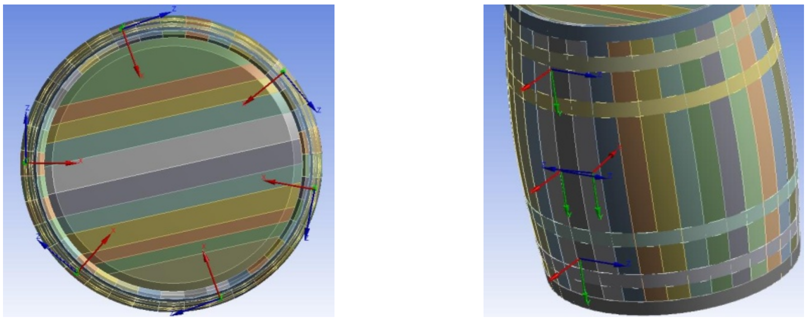

Figure 2: FEA displacement probes about the barrel bilge

3 Results and Discussion

3.1 Oak Material properties

Figure 3 displays the experimental analysis of the oak timber materials used in barrels. The analysis is quoted with the grain orientation of concern against the loaded grain.

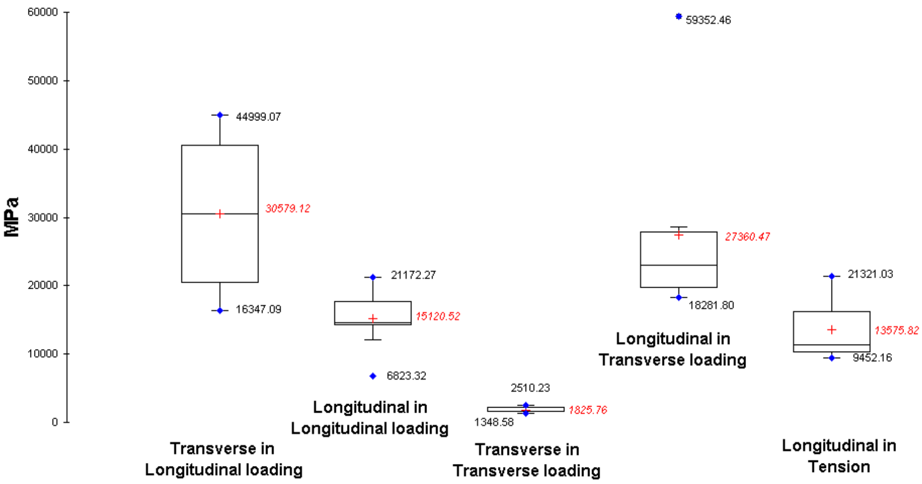

Figure 3: Material properties of barrel oak

The analysis showed large variation in the transverse and longitudinal MOE values. This can be attributed to the natural variation in both the timber and the previous use of the staves in the barrel.

The average property values from the analysis (longitudinal: 15000 MPa and transverse: 1800MPa) were those used in the orthotropic FEA modelling of the full-scale barrel. The values used correlated well with those available in literature (U.S Department of Agriculture 1999) and were therefore deemed valid.

3.2 Experimental structural analysis

Using the horizontal displacement of the staves measured, a stiffness rating was calculated based on Equation 1. An average stiffness rating for thinned barrels was calculated based on the 8 staves analysed. Figure 4 shows the relationship between the calculated stiffness rating and the thickness of the staves within the barrel.

$$E = \frac{\Delta F}{\Delta w}$$ Equation 1

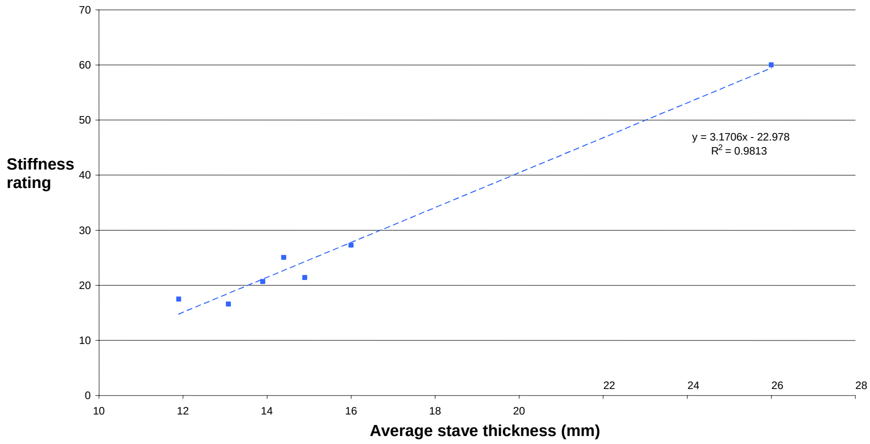

Figure 4 – Stiffness rating comparison of thinned barrels

The correlation between stave thickness and stiffness rating has R^2 value of 0.98. The regular barrel thickness was used to validate the FEA model, however optimised hoop arrangements can be used to increase both thinned and regular barrels.

3.3 FEA

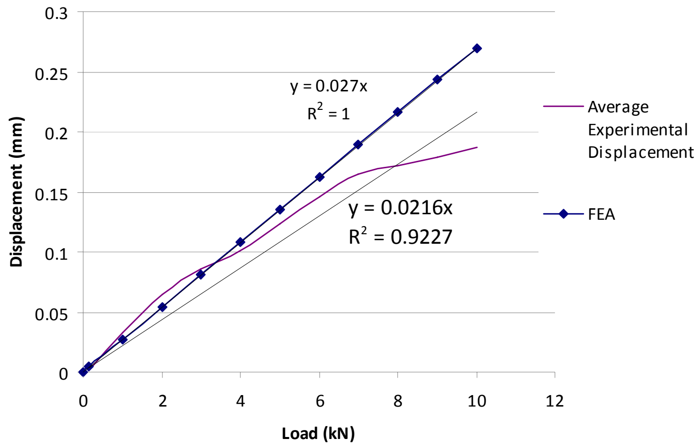

Figure 5: FEA model validation

The stave displacement measurements for the barrels of regular stave thickness (approximately 26mm) are shown in Figure 5 in a comparison to the FEA model prediction. Based on the natural variation in mechanical properties of the oak timber (as shown in section 3.1) the model was deemed valid for use in optimisation of hoop arrangements.

Figure 6 shows the FEA representation of the stress distribution for a regular barrel with a current hoop arrangement. A stress concentration about the centre of the staves (the bilge) is observed together with a high concentration of stress on the bilge hoops for the current barrel providing an FEA stiffness rating of 39. FEA results were acquired by measuring an average stave displacement between the centre line and 250mm above and below. The average displacement at three locations about the stave shows the overall effect of relocating the hoops and ensures the load is distributed evenly about the barrel components with no alternative stress concentrations being created. Figure 7 shows the comparative analysis of the FEA stiffness ratings for each of the hoop arrangements (outlined in 2.3)

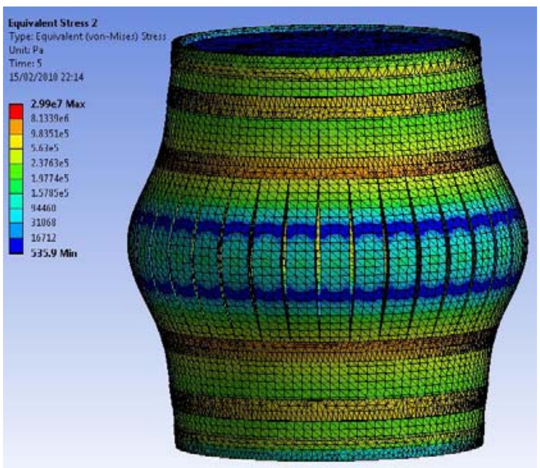

Figure 6: FEA image of stress distribution for current barrel hoop arrangement

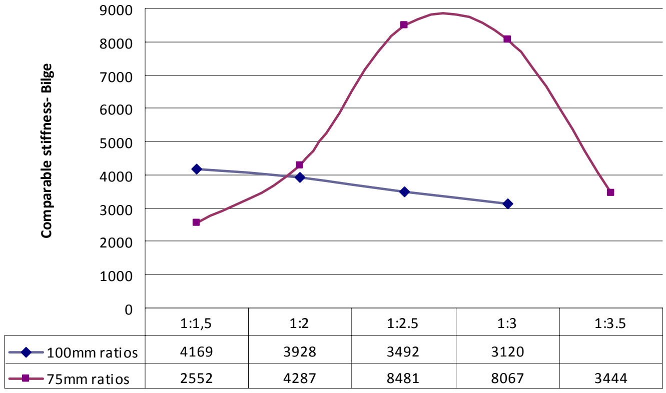

Figure 7: Comparative stiffness analysis for 75mm and 100mm bilge hoop locations

The comparative stiffness analysis between the 100mm and 75mm bilge hoop arrangements show that the 100mm was initially greater than the 75mm arrangement. However, the 75mm continued to increase up to a 1:2.5 ratio while the 100mm decreased from the start. This is due to the effect of the quarter hoop on stiffness as it is relocated. At the 1:2.5 ratio in the 75mm hoop arrangement the hoop arrangement is optimised with respect to the transfer of load from the tangential to the longitudinal timber property as the hoops absorb stress by reducing lateral stave displacement. The 75mm hoop arrangement was then compared to the current barrel with respect to their stiffness ratings (shown in Figure 8).

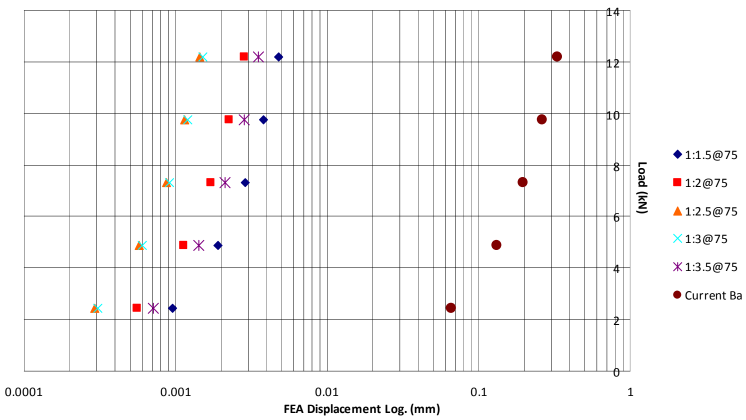

Figure 8: FEA of average stave displacement for defined hoop locations in 75mm analysis

Optimising the hoop arrangements and reducing lateral stave displacement has increased the stiffness rating of the barrel by a factor of approximately 1000. A FEA stress distribution of the optimised hoop arrangements is shown in Figure 9. The optimised barrel shows no extreme stress concentrations as a result of the stress being distributed across all components and transferring stress from the weaker tangential to the stronger longitudinal timber properties.

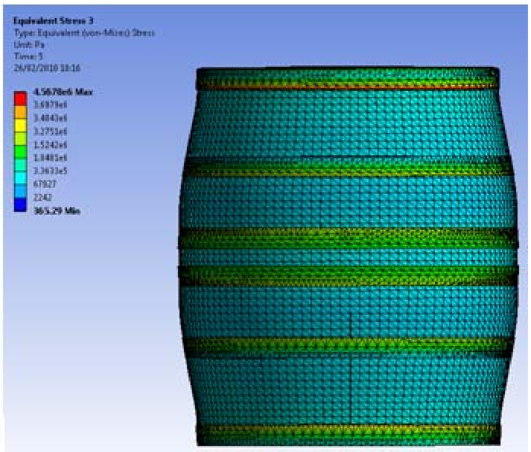

Figure 9: FEA image of stress distribution for optimised 1:2.5

4 Conclusions

The relocation of the hoops to these positions about the barrel has created a lateral transfer of stress from the timber staves to the steel hoops. By placing the bilge hoop close to the centreline of the barrel a significant degree of stress is noted. However, by locating hoops to a 1:1.5 ratio, the area between quarter and end hoops becomes significant enough to transfer the stress to upper and lower areas of the barrel staves. By locating the quarter hoop to a location that stave stress is transferred in an even distribution to all steel hoops, the overall stiffness of the barrel is optimised. By re-locating the current barrel hoops to the optimised locations, the overall stiffness of the barrel has been increased by a factor of 1000.

The mechanics that have allowed such a large increase in structural stiffness are the transfer of stress on the timber to the supporting steel hoops by increasing lateral support of the barrel and effectively distributing the overall stress experienced by the structure evenly between the individual components, or to components with the greatest strength. The steel hoops have a much larger MOE property than the timber so increasing their efficiency in absorbing stress results in an overall increase in structural stiffness.

The efficiency of the hoops in absorbing stress occurs when they are placed in such a manner as to transfer the stress the staves are placed under when displacement at the weak point of the bilge occurs. When the bilge of the barrel displaces, the timber is effectively under bending whereby the tension component relies on the transverse MOE property of the timber, which is a factor of ten less than that of the longitudinal MOE. Therefore the stress concentration about the bilge instigates de-lamination of the timber and failure of the barrel at a much lower load. Introduction of the bilge hoop to this location transfers the stress to the stronger steel component of the barrel. The remaining stress the timber experiences is now transferred from the tension component of the transverse grain to the compression component of the longitudinal grain. With the longitudinal grain having a greater MOE value than the transverse grain by a factor of ten, the overall structural stiffness in now dependent upon the strongest components of the barrel (i.e. steel hoops and longitudinal grain).

Future barrel construction should firstly relocate the datum of hoop locations to the centreline of the barrel to reduce the variability of hoop efficiency on structural integrity. In addition to this the bilge hoop should be placed at a distance from the bunghole of 15% of half the barrel height (75mm in this investigation). The quarter hoops should then be placed at a ratio of 1:2.5 of this distance between the centre line and end hoops. With the improvement in the efficiency of the barrel components, the structural integrity of the barrel is increased for palletised warehousing of thinned barrels.

5 References

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