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Optimisation of an oak container

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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. Changing and challenging demands in the storage of barrels with respect to increased loading applied in a non-traditional direction has led to a need for the optimisation of the structure's integrity. 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.

KEYWORDS: Barrels, Timber, Finite Element Analysis, Structural integrity

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 [1]. However, the original design concept of a barrel was to provide a container capable of transporting large loads with minimal effort. This requirement of the barrel is somewhat removed from the modern-day operations and it is used in areas such as the maturation of alcoholic spirits. Evolution of warehousing and transport technology, such as forklifts, and consequently barrels are stored vertically in palletised warehousing instead of the traditional horizontal storage. This raises concerns to the structural integrity of the barrel structure with the additional loading. These concerns are amplified with respect to 'thinned' casks becoming more common, especially within the wine and spirits industries.

The coopering industry is a very traditional profession with skills passed from generation to generation, and much knowledge gained prior to this investigation was acquired through the experience of coopers. Limited literature is available regarding the precise construction specifications (i.e. dimension, method of manufacture etc.) as a result of such a traditional profession. Hoop locations about the cask are therefore very subjective and left to the discretion of the individual cooper with the 'rule-of-thumb' being quarter hoop 'three fingers' from the end hoop, and the bilge hoop 'a third' of the cask height down from the end hoop. This subjectivity, and the possible impact of structural integrity, is further amplified with the variation in barrel height. By using the end hoops as a datum point for the location of the quarter and bilge hoops results in the stress concentration about the centre of the barrel begin increased in barrels with taller staves. This is due to the reduction in lateral support provided by the two main bilge hoops as a result of the increased distance between barrel centre line and hoops.

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Research into barrels has been conducted in the past, however the structural integrity aspect are not considered as the data was collected prior to palletisation warehousing [2]. As a result, recommendations for optimisation of the structural integrity for traditional barrel were not investigated and therefore no gains to the current body of knowledge were made.

Traditional oak barrels have evolved over their life rather than step changed effectively as a result of the traditional methods of manufacture being subjective. However, there have been efforts to optimise the barrel with respect to retention and vacuity issues. Square barrels have been the focus of many redesigns of the traditional barrel [3][4], for reduced warehouse vacuity, and even complete lamination of the structure [5] to compensate for the brittle effects caused by kiln drying and use on inferior timber with the perceived potential of sources becoming scarce. However, with barrels being used in such large quantities it is difficult to transform the overall geometry of the barrel and modify with respect to the additional components (i.e. more hoops). This investigation aims to optimise the current barrel structure by increasing the structural stiffness under vertical loading by re-locating the existing hoop to specific locations using finite element analysis, augmented with a series of experimental studies.

2 Methodology

In-order to produce a valid FEA model experimental data was required for both the timber material properties and the barrel structure in its current form. The data acquired from material properties testing and structural analysis of the complete barrel was then used to produce a valid model for assessing the effect of various hoop arrangements in the FEA environment.

2.1 Experimental

2.1.1 Oak material properties

Timber properties vary hugely depending upon origin of growth and operating conditions. Consequently, material properties associated with oak barrel required quantification. Employing EN 408 standards [6], 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.

2.1.2 Structural analysis

Structural analysis of a current barrel was conducted to show the load-deformation characteristics for FEA validation. Displacement transducers were placed around the centreline of the barrel bilge to monitor deformation of global circumference. Displacement in stave bilge around the barrel is due to the stress concentration at the weakest components (transverse grain of the stave under tension) about the barrel and therefore requires optimisation. *Figure 1* shows the schematic of displacement transducer locations about the barrel bilge for monitoring stave displacement.

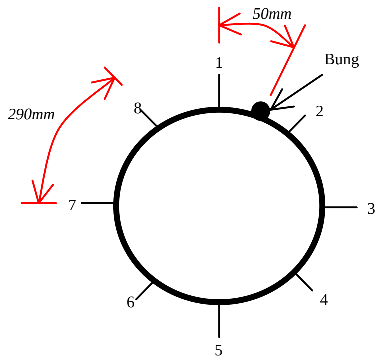


***Figure 1**: Schematic on displacement transducers about the barrel bilge*

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 were tested in total with average displacements being used for analysis.

2.2 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 develop 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 cask (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 cask 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 form 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.

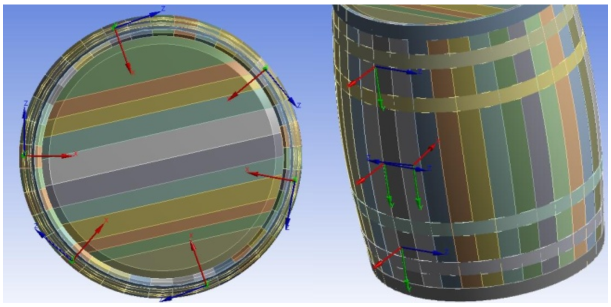


Figure 2: *FEA displacement probes about the barrel bilge*

3 Results

3.1 Experimental

3.1.1 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.

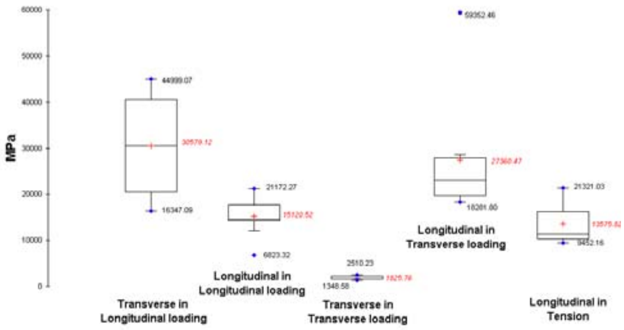


Figure 3: *Material properties of barrel oak*

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 [7] and were therefore deemed valid.

3.1.2 Structural analysis

The analysis of the bilge displacement under load for probes 1-8 (as outlined in *Figure 2*) is shown in *Figure 4*. Probes 1-4 show an increase in displacement in relation to increased loaded. However, probes 5-8 show a decrease showing the movement of staves inwards. This was attributed to misalignment of staves during construction (a common feature of traditional barrels) and the consistency of the floor level. Consequently, only the four probes with increases in stave displacement were used for validation of the FEA model.

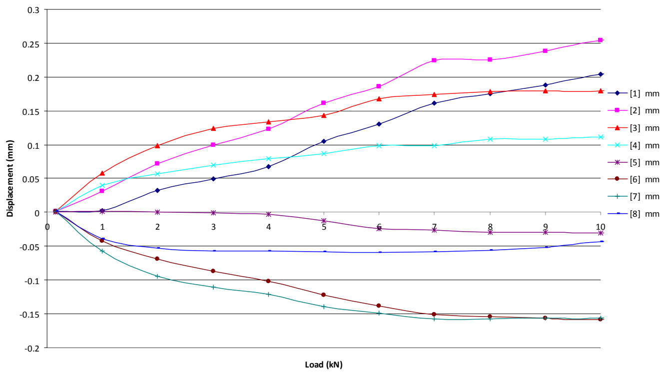


Figure 4: *Cask bilge displacement under load*

Analysis of the experimental data aligned to the EN 408 [6] with respect to the elasticity gradient between 0.1 and 0.4 of the maximum load gave a comparative stiffness value (a non-unit rating) for each displacement probe. The comparative analysis showed an average stiffness rating of 60.4 with a standard deviation of 21.5 showing the overall stiffness of the barrel together with the variation present brought about by variations in timber properties and the imperfections created during manufacture of the barrel.

3.2 Finite Element Analysis

Prior to optimisation of barrel stiffness, the FEA model required validation against experimental data. Taking the average displacement about the bilge from the experimental data and correlating with the FEA of the barrel with hoop locations at a similar locations (from the centre line of the barrel, 275mm and 400mm for the bilge and quarter hoop respectively), validation of the numerical model was possible, as shown in *Figure 5* The comparative stiffness rating of the FEA model is 37. This is not within the 10% limits of the experimental average of 60.4. However, it is well within the range of the experimental analysis. Changes to the material properties at this stage could have been considered, however, the natural variation of timber properties as described in *Figure 3*, show the difficulty in acquiring an exact model. However, this was an accurate model that will provide comparisons of hoop arrangements that are transferable to experimental analysis and was therefore deemed valid.

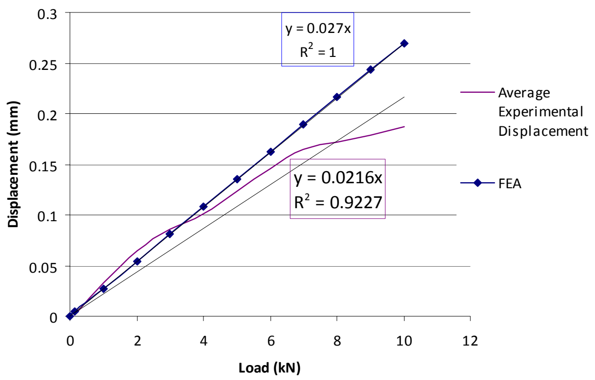


Figure 5: *FEA model validation*

Figure 6 displays the corresponding stress distribution of the current barrel in the FEA analysis to a 40x deformation scale. *Figure 7* shows the displacement values for the bilge probes in the 75mm analysis with respect to various hoop arrangement ratios (as explained in 3.2)

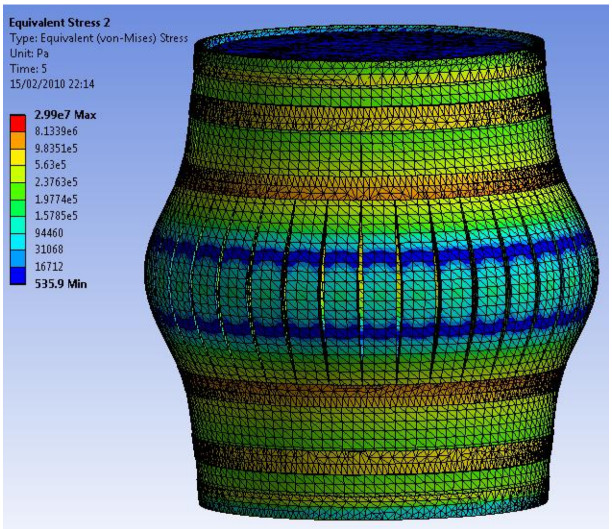


Figure 6: *FEA image of stress distribution for current barrel hoop arrangement*

The FEA 75mm analysis of bilge displacement (*Figure 7*) shows that the 1:2.5 hoop arrangement provided the greatest increase in comparable stiffness rating of 8950 compared to the current cask stiffness of 37. However, the effect of the four individual hoops (2x bilge and 2x quarter) under investigation is not integrated into this particular analysis and the stiffness values are not true of the entire structure. To show the effect of all four hoop locations on the entire structure a further analysis was carried out, *Figure 8*, whereby the average displacement of the upper, centre and lower stave probes (displayed in *Figure 2*) are used to calculate a comparative stiffness value. This stiffness rating is compared to that using only the bilge displacement.

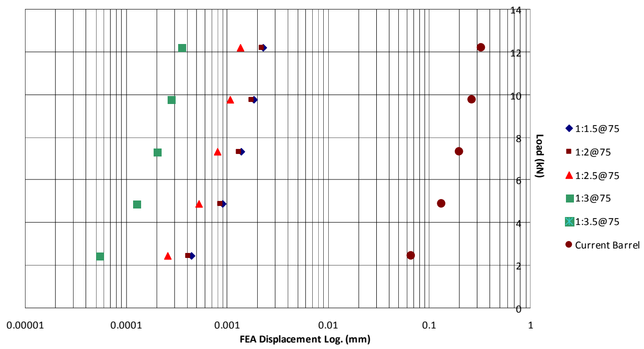
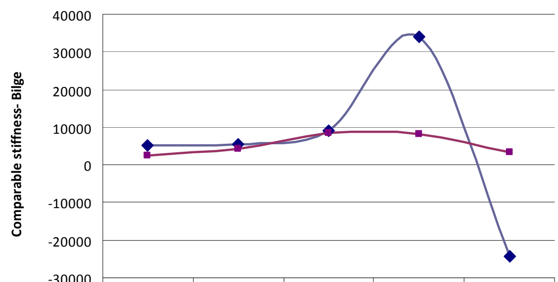


Figure 7: *FEA of bilge displacement for defined hoop locations*

This analysis of the average displacement across the entire stave highlights the influence of the quarter hoop in increasing/ decreasing the structural stiffness of the barrel. This is shown by the comparable stiffness using just the bilge displacement where a significant increase at the 1:3 ratio and then a dramatic drop at 1:3.5 ratio occurs. This is caused by the shift of stress concentration from the bilge to the upper and lower portions of the barrel. Once the quarter hoop is passed the 1:2.5 distance it becomes dramatically inefficient at providing lateral support, causing the upper and lower stave portions to absorb the load and displace horizontally outwards from the cask. The effect on overall stiffness becomes amplified as the bilge of the barrel actually displaces inwards as a consequence of this shift in the stress concentration rather than a transfer to the lateral supports. The overall stave displacement is therefore a more valid measurement of the transfer of stress to the supporting hoops, as shown in *Figure 8*.



	1:1.5@75	1:2@75	1:2.5@75	1:3@75	1:3.5@75
Bilge displacement	5282	5545	8950	33903	-24361
Overall Stave displacement	2552	4287	8481	8067	3444

Figure 8: *Comparison of bilge and overall stave displacement analysis*

Figure 9 shows the comparative analysis of structural stiffness for various quarter hoop ratios with 75mm and 100mm bilge hoop positioning. It can be seen that the 100mm bilge hoop location never reaches the stiffness provided by the 75mm placement. This is as a result of the 75mm placement situated closer to the stress concentration of about the bilge and therefore a more effective transfer of stress is possible. In addition to this the effect of the quarter hoop on lateral support becomes quickly redundant in the 100mm analysis. As the 75mm bilge hoop placement if optimal, further analysis will be focused on the quarter hoops ratios associated with this bilge hoop location.

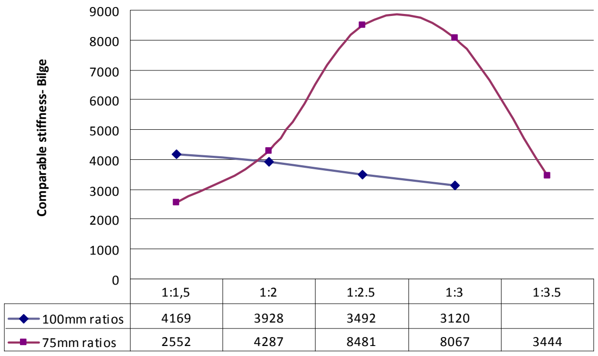


Figure 9: *Comparative stiffness analysis for 75mm and 100mm bilge hoop locations*

Figure 10 shows the overall stiffness comparison between the ratios at a bilge hoop distance of 75mm against the current barrel analysis. The 1:2.5 ratio shows the maximum stiffness with a comparable rating of 8481 against the 37 of the current barrel.

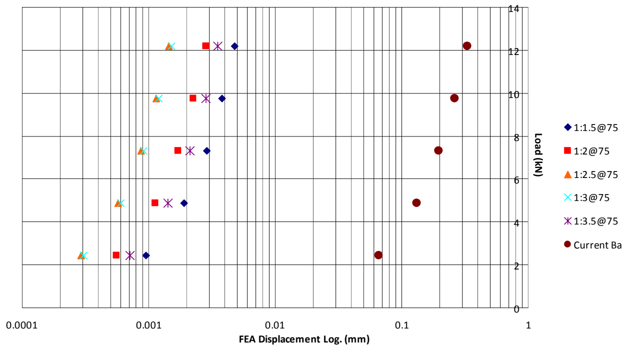


Figure 10: *FEA of average stave displacement for defined hoop locations in 75mm analysis*

4 Discussion & Conclusions

The valid FEA model (example image shown in *Figure 11*) showed the placement of the hoops to the 1:2.5 ratio of hoop to centre line distance was the optimised location for increasing the overall stiffness of the barrel structure with comparative ratings of 37 and 8950 for the current and optimised barrels respectively.

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 transferred. However, by locating hoops to a 1:1.5 ratio, the area between quarter and end hoops becomes significant enough to transfer the about the bilge upper and lower areas of the barrel staves. By locating the quarter hoop 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 cask hoops to the optimised locations, the overall stiffness of the barrel has been increased by a factor of 1000.

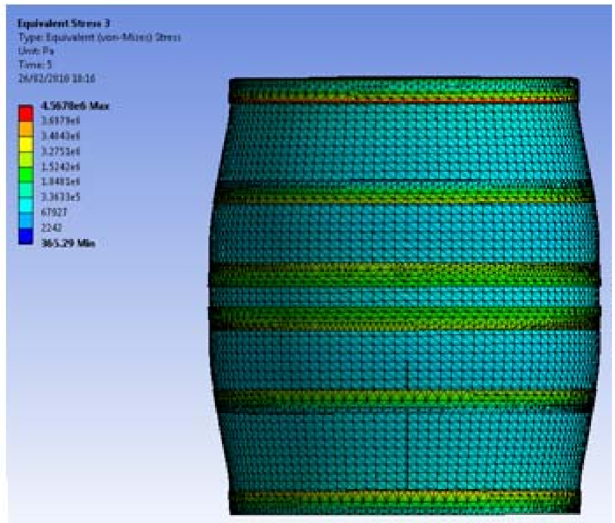


Figure 11: *FEA image of stress distribution for optimised 1:2.5*

The mechanics that have allowed such a large increase in structural stiffness are the transfer of timber stress to the 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 displacing at the weak point of the bilge. 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 bung hole 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.

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