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Analysis of Crack Propagation in an Adhesive Joint

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ABSTRACT

Adhesive joints are widely used in industries because they have several advantages when compared to welded and riveted joints. One of the important factors is that they distribute the load and stresses uniformly over the entire bonded area providing good vibration resistance. Adhesive joints can readily bond dissimilar materials. The prediction of crack propagation validating the adhesive joint durability and toughness is a significant point which is addressed through various experimental methodologies based on the type of loading conditions. The analysis is hindered by the unpredictable substrate and adhesive behavior due to the loading conditions, the nature of crack propagation, and the geometry. The impact of hardener resin ratio alteration is a parameter which needs to be explored in validating the joint toughness. The Double Cantilever Beam tests which are used for analyzing the fracture toughness for mode-1 loading in adhesive joints focus on adhesive thickness variation extensively. The alteration of composition and its role in influencing the crack propagation is explored in a limited perspective. An attempt is made in this work to analyse the adhesive composition variation and its impact on the joint toughness with the help of a DCB test involving three specimens incorporating variations in the hardener resin composition. The analytical and the experimental results provided significant insights on the adhesive joint toughness validation.

Keywords: double cantilever beam, strain energy release rate.
Introduction

Adhesive joints are known for their ability to achieve uniformity in load and stress distribution characteristics over the entire bonding region in engineering applications. They are preferred over other mechanical joints due to their fatigue resistance, crack retardation, galvanic isolation, vibration damping, and enhanced sealing capacity. The validation of adhesive joints is done by determination of the nature of crack propagation which requires suitable methodology. The nature of crack propagation in an adhesive joint depends widely on the loading conditions, and the hardener-resin proportion variation of the adhesive composition. The mode-1 loading conditions are more prevalent in adhesive bonding between similar and dissimilar substrates. Hence an analysis is done to estimate the nature of crack propagation under mode-1 loading conditions and variation in the hardener-resin proportion using the Double Cantilever Beam (DCB) test involving mild steel substrates and the results are presented.

Role of DCB Tests

The DCB test is used to analyze the fracture behavior of adhesive joints under mode-1 loading. This test involves the measurement of the Strain Energy Release Rate (SERR or $G_c$) for the mode-1 loading. Some of the most prominent literatures revealing the relativity of the DCB test for the mode-1 loading is listed. Fan.C et al. [1] used the DCB test for the measurement of fracture toughness of FRP for the mode-1 loading. The experimental results were compared with the energy release rate values from the analytical methods. Andersson.T et al. [2] used the DCB test for measurement of the cohesive properties of an adhesive joint. Freed.Y et al. [3] used a DCB specimen for prediction of the crack formation under mode-1 loading of adhesive joints involving laminated composite substrates. The fracture behavior of adhesive joints was explored by using both DCB and tapered DCB specimens by Marzi et al. [4]. Morais et al. [5] used the DCB test to scrutinize its effectiveness when considering its application in the form of determining the fracture toughness under mode-1 loading of the cortical bone tissue. Yoshihara et al. [6] considered the DCB test due to its effectiveness in his work involving the calculation of the strain energy release rate ($G_{ic}$) in the process of estimation of critical stress intensity factors of wood. C.J. Constante et al. [7] used the DCB tests to estimate the strain energy release rate for specimens between Aluminium adherents and adhesives with varying measures of ductility.

Some of the literatures pertaining to the variations in hardener-resin proportion variation are also listed as follows. Satheeshkumar et al. [8] investigated the influence of hardener-resin ratio changes on the behavior patterns of adhesive-bonded steel DCB specimens. The work involved the usage of both epoxy and acrylic adhesives whose hardener and resin ratios were varied. The research led to the conclusion that the transition from resin dominance to hardener dominance...
improved the ductility of the adhesive layer, improvement in the elongation and yield strains of the substrates. Kulkarni [9] conducted a FEA analysis to highlight the influence of resin hardener ratio change from 1:1 to 2:1 on the sustained force for both adhesive and hybrid joints. Rupa [9] explored the response of a transducer to different bond strengths by considering the variations of 1:1 and 1:4 hardener-resin ratio in the selected adhesives and simultaneously maintained the consistency of the bond-line thickness.

Scope of the Present Research Work
The research work shown in the paper explores the parameter of hardener-resin proportion variation of the adhesive bonding between steel substrates. The prominent loading conditions were selected as mode-1 loading and the DCB test based on the justification from the literature was utilized for this purpose. The work aims to work on a limitation in the previous works which did not consider the hardener-resin proportion variation as a significant parameter when conducting delaminating studies between similar as well as dissimilar substrates.

Relations Used
The determination of mode I fracture toughness (G_c) is the objective of the DCB test. This involves generation of plots between the applied load and the crack length for the three composition altered specimens comprising mild steel substrates. Subsequent analysis involves plot generation between critical strain energy release rate against the crack length which in turn generates the delamination resistance curve or R curve as specified by ASTM D5528-01. The G_c calculation from the DCB test is done by considering the simple beam theory and suitable experimental compliance from equations (1) and (2).

The following equations are considered for obtaining the value for G_c:

\[ G_c = \frac{1}{2B} \frac{P^2}{\delta} \frac{dc}{da} \]  
(1)

\[ G_c = \frac{12P^2a^2}{E_sB^2h^3} \]  
(2)

\[ G_i = \frac{3P\delta}{2B(\alpha+\betaJ)} \]  
(3)

The equations (1) and (2) are based on the simple beam theory and the equation (3) is based on the corrected beam theory where ‘P’ denotes the applied load, ‘a’, the crack length, ‘dc/da’, the degree of compliance, ‘E_s’, the elastic modulus of the mild steel substrates, ‘b’, the specimen width, and ‘h’, the specimen thickness.
Experimental Details
The present work analyses the results of a DCB test done on an adhesive joint having mild steel substrates and Araldite adhesive. The selection of mild steel over Aluminum as substrate material is due to the presence of a larger plastic zone in steel compared to Aluminum as outlined by Azari et al. [10]. The increase of adhesive plastic dissipation inside the full plastic zone was more in steel compared to aluminium as suggested by Pardoen et al. [11]. Hence the substrates were selected as mild steel in the DCB specimen geometry which is based on ASTM D5528-01.

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Young’s modulus (E)</td>
<td>2.1 \times 10^5 MPa</td>
</tr>
<tr>
<td>2</td>
<td>Poisson’s ratio (μ)</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>Density (ρ)</td>
<td>7850 kg/m³</td>
</tr>
</tbody>
</table>

Table 1: Substrate properties

The specimens are joined using the epoxy resin Araldite LY 556 and the anhydride hardener HY 906. The adhesive is selected for its ability to perform under elevated temperatures and good fatigue resistance. Several literatures including R. Kottner et al [13], T.Nishioka et al. [14] validate the selection of the Araldite epoxy resin.

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Property</th>
<th>Value</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tensile strength</td>
<td>55 Mpa</td>
<td>ISO 527</td>
</tr>
<tr>
<td>2</td>
<td>Flexural modulus</td>
<td>3000 Mpa</td>
<td>ISO 178</td>
</tr>
<tr>
<td>3</td>
<td>Shear strength</td>
<td>70 Mpa</td>
<td>ASTM_D 2344</td>
</tr>
</tbody>
</table>

Table 2: Araldite properties [12]

Figure 2: ASTM Standard [9]
Variation of Adhesive Composition
The bonding surfaces of the steel substrates are scrubbed with sand paper and wiped with acetone for contamination removal. This is done to facilitate consistent load transfer and to avoid separation.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>% of Hardener -Resin</th>
<th>Hardener (ml)</th>
<th>Resin (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>50% - 50%</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>B</td>
<td>60% - 40%</td>
<td>2.5</td>
<td>37.5</td>
</tr>
<tr>
<td>C</td>
<td>70% - 30%</td>
<td>2.5</td>
<td>58.3</td>
</tr>
</tbody>
</table>

The DCB specimens incorporating the composition alterations as specified in table 3 were initially kept under dead weight for 8 to 10 hours. Subsequently, they were clamped in a machine vice for an entire day and dried completely before subjecting for analysis. The adhesive thickness was maintained using a Teflon insert at 1mm in all the three specimens. The pre-crack length was kept as 25 mm as per the ASTM standard D5528-01. A spring actuated fixture as shown in the diagram is used to clamp the DCB specimen in a tensile testing machine. The tensile testing machine comprises of a digital encoder, and a gear rotational speed facility for systematic loading and unloading. The DCB specimens were loaded at a constant displacement rate of 1 mm/min.
Results and Discussion

The load displacement curves are separately obtained from the digital read out directly from the tensile testing machine for the three DCB specimens A, B and C.

Figure 6: P-δ curves obtained from digital read-out of the UTM separately for the 3 specimens
Table 4: Range displacement tabulation

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Maximum load (KN)</th>
<th>Crack length (mm)</th>
<th>Load range (KN)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.18</td>
<td>0.3</td>
<td>0 - 0.162</td>
<td>0 - 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.162 - 0.18</td>
<td>0.2 - 0.3</td>
</tr>
<tr>
<td>B</td>
<td>0.43</td>
<td>1.2</td>
<td>0 - 0.4</td>
<td>0 - 1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.4 - 0.43</td>
<td>1.1 - 1.2</td>
</tr>
<tr>
<td>C</td>
<td>0.48</td>
<td>2</td>
<td>0 - 0.46</td>
<td>0 - 1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.46 - 0.48</td>
<td>1.8 - 2</td>
</tr>
</tbody>
</table>

Table 5: $G_c$ calculation from Simple Beam Theory given in equation [1]

<table>
<thead>
<tr>
<th>Specimen A</th>
<th>Specimen B</th>
<th>Specimen C</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (mm)</td>
<td>P (KN)</td>
<td>$G_c$ (KN/m²)</td>
</tr>
<tr>
<td>0.1</td>
<td>0.03</td>
<td>1.80</td>
</tr>
<tr>
<td>0.3</td>
<td>0.15</td>
<td>1.50</td>
</tr>
<tr>
<td>0.4</td>
<td>0.17</td>
<td>1.45</td>
</tr>
<tr>
<td>0.5</td>
<td>0.05</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>0.05</td>
<td>0.50</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td>0.05</td>
<td>0.17</td>
</tr>
<tr>
<td>3.2</td>
<td>0.05</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table 6: $G_c$ calculation from Simple Beam Theory given in equation [3]

<table>
<thead>
<tr>
<th>Specimen A</th>
<th>Specimen B</th>
<th>Specimen C</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (mm)</td>
<td>P (KN)</td>
<td>$G_c$ (KN/m²)</td>
</tr>
<tr>
<td>0.03</td>
<td>0.1</td>
<td>1.023</td>
</tr>
<tr>
<td>0.15</td>
<td>0.3</td>
<td>5.443</td>
</tr>
<tr>
<td>0.17</td>
<td>0.4</td>
<td>6.219</td>
</tr>
<tr>
<td>0.05</td>
<td>0.5</td>
<td>1.838</td>
</tr>
<tr>
<td>0.05</td>
<td>1</td>
<td>1.856</td>
</tr>
<tr>
<td>0.05</td>
<td>2</td>
<td>1.866</td>
</tr>
<tr>
<td>0.05</td>
<td>3</td>
<td>1.867</td>
</tr>
<tr>
<td>0.05</td>
<td>3.2</td>
<td>1.869</td>
</tr>
</tbody>
</table>
Figure 7: Consolidated P-δ curves for the 3 specimens

Figure 8: Strain Energy Release Rate ($G_{ic}$) vs crack length (a) based on Simple Beam theory
Initially, the three load displacement curves are taken separately from the UTM as shown in the Figure 6. The three curves obtained separately from the digital read-out facility of were consolidated for the three specimens shown in Figure 7. Furthermore, the strain energy release rate ($G_{ic}$) vs the crack length which constitutes the R curves was plotted for the three specimens in Figure 8.

**Observations Due to Hardener-resin Proportion Variation in the Adhesive Layer**

The observations reveal the effect of the increase in the resin composition on the load applied and the corresponding crack length in the 3 dcb specimens. In all the three types tested, the analysis involved monitoring the propagation of the crack simultaneously as the load-displacement data was plotted. The crack retardation was erratic for the first 15 mm for the first specimen which had an equal proportion of hardener-resin mixture. The remaining two specimens which had 60:40 and 70:30 showed an equal rate of propagation which lead to the finalizing of the nature of the crack as cohesive. The cracks were not found to propagate into the substrate regions for all the three specimens. Finally the conclusion of the crack propagation resulted in total detachment of the steel substrates.
Discussions and Related Attributes to the Hardener-resin Proportion Variation

The P-δ curves obtained for the three specimens show convergence and marginal deviation to some extent. The Strain Energy Release Rate vs the crack length which are the R curves are drawn using the tabulations from the Simple and Corrected beam theories. The plots (Figures 8 and 9) reveal the peak values for the $G_{ic}$ for the specimen B which indicates the influence of the resin dominance in the adhesive composition. In all the three experimental curves in the P-δ plot, the initial linear region coincides with the obtained values. The sudden reduction in load after the peak value is attributed to an unstable crack growth during its initiation. The curve continues as linear until the starting of crack propagation which is due to the exceeding of the crack driving force over the fracture toughness of the specimens used. The R curve plotted shows a linear rise followed by a plateau level which indicates initial elastic behavior followed by crack length increment for all the three specimens.

Figures 7, 8 and 9 show pronounced variations and clear differentiations of the performance of the three specimens attributed to the variation in the hardener-resin proportion. The attempt to study the propagation is quite successful incorporating the hardener-resin proportion variation with the help of the P-δ and the R curves plots.

Research Contributions Derived from the Work

The linkage between bonding of similar substrates and the proportion variation of the hardener and the resin was addressed in the form of effective implementation of the DCB test subjected to the mode-1 loading conditions. The scope of the other works in the realm of mide-1 testing was limited to non-consideration of the proportion variation of the adhesive selected. The present research work aims to remove this limitation by considering the three suitable variations in the proportion of the hardener-resin ratio. The two theories of $G_{ic}$ calculations which were the Simple and Corrected beam theories provided insight as to how the influence exerted by the proportion variation impacted the bonding characteristics of the selected adhesive under more-1 loading conditions. It is clearly visible that the linkage between the similar substrate bonding and the proportion variation impacted the $G_{ic}$ values obtained from both the beam theories as highlighted in the plots.

Conclusion

An experimental attempt was made to study the nature of crack propagation in the conducted DCB test for mode-1 fracture in the adhesive joints. The DCB tests were conducted incorporating hardener resin proportion variation as an investigating parameter. The characteristics of crack propagation in the adhesive layer under the
influence of hardener-resin proportion variation were analyzed. The results indicate the dominance of the resin proportion which was visible from the R curves plotted for the three specimens incorporating the Simple and Corrected Beam theories. The analysis of the results was significant as they highlighted the retardation of the crack for the specimens B and C which was seen from the peak Strain Energy Release Rate values from the plots.

References


Analysis of the Thermal Behavior of the Double Skin Envelope in the Full Scale Testing Modules of the Postgraduate Unit for a Cloudy and a Clear Day

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Leonardo B. Zeevaert Alcántara
Master Program in Architecture National, Autonomous University of Mexico

ABSTRACT

At the campus of the National Autonomous University of Mexico, on the roof of the "J" building of the Postgraduate Unit (19°18’33.59"N,99°11’5.73"O), an Observation Deck and Experimentation Laboratory of the Master and PhD Program in Architecture are installed. This platform consists of two Full Scale Testing Modules. Each module has 9.00 m² of floor and 3.00 m high. The vertical envelope is formed by a double layer envelope with exterior and interior insulation. The horizontal envelope (cover) has insulation and a waterproof pre-manufactured system. The horizontal envelope (floor) has insulation outside and inside the structure as well as a radiation barrier. Data from each sensor was recorded every minute. The aim of this research is to characterize the thermal behavior of the Full Testing Modules; we are looking for thermal stability 24 hours a day. In order to do that, the first phase was to determine which of the measured variables directly affects the temperature of the inner side of the envelope. The obtained data was compared and showed that on a cloudy day, the global radiation does not interfere directly in the thermal behavior of the inner part. In this stage, the internal temperature of the module is directly related to the temperature inside the envelope. For a clear day we got that, the global radiation does interfere in the temperature of the inner face of the envelope, but is even more direct the relationship of the temperature inside the module with respect to the envelope temperature.

Keywords: full scale testing module, thermal behavior, double layer envelope, temperature measurement, variable correlation.
**Introduction**

Of the 290 investigations that have been conducted on the Technology field of the Master and PhD Program in Architecture since 1973, the 62.42% (181 theses) have been focused on Environment and Energy issues as well as Development of Materials and Systems. Most part of this research required to check its arguments with in an experimental space designed by each researcher according to the specific needs of their projects. This situation greatly complicated the continuity of certain research lines and the testing of hypotheses expressed in the research. The Program needs to create an experimental space that meets the needs of most of the researchers and which can give continuity to the opened research lines.

At the roof of the “J” building of the Postgraduate Unit belonging to the campus of the National Autonomous University of Mexico, we located the Observation Deck and Experimentation Laboratory of LIM. This platform consists of two Modules of Experimentation. Each module has 9.00m² of floor and 3.00m high. The vertical envelope is formed by a double layer envelope with exterior and interior insulation. The horizontal envelope (cover) has insulation and a waterproofing pre-manufactured system. The horizontal envelope (floor) has insulation outside and inside the structure as well as a radiation barrier.

![Figure 1: Full Scale Testing Modules](image)

One of the vertical faces has a span in which the Experimental Façade is placed, which is where the experiments were installed. Each module is set on a special structure that allows them to rotate 360 degrees on its axis, which gives the opportunity for each one of its facades to be observed in any orientation.
Outside the Observation Deck there are instruments to measure meteorological variables such as Temperature, Relative Humidity, Irradiance, and Illuminance. Data was collected every minute using a data acquisition system. In the Experimentation Modules, data loggers of Temperature and Relative Humidity were installed, which recorded data on the internal conditions of the modules. The measurements obtained on both platforms (internal and external) for a clear day and a cloudy were analysed. Data was processed to validate their correlation.

Aim

To reach temperature stability inside the test module, we analyse and compare the measured meteorological data from the outside, with those obtained within the platform of Experimentation, we can understand the incidence of Solar Radiation on the envelope and the relationship related to the increase or decrease in temperature on the inner face of the outer layer of this. The increase of the indoor temperature is a function of outside air temperature and the heat-bound constructive configuration of the envelope.

With this exercise, we intend to evaluate which is the thermal effect of the interior of the module, the radiation incident on the south façade, and behavior of the insulation of the outer layer of the envelope, both for a cloudy and a clear day.

Measurements

The Observation Deck and Experimentation Laboratory of LIM are located in the roof of building J of the Postgraduate Unit. Its location as UTM coordinates is: QZone14, Easting 480541.14mE, Northing 2135054.19m N.

For the measurement of the variables outside, measuring instruments were connected to a data acquisition system, records were taken every minute and the data was processed. The measurement period for this exercise was from March 23 to March 31, 2015.

Coming up next, there is a list of the installed equipment, the variables that are recorded and measurement units which we worked with.
Table 1: Equipment list set out side

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Trademark</th>
<th>Model</th>
<th>Parameter</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyranometer</td>
<td>Kipp&amp;Zonnen</td>
<td>CMP-21</td>
<td>Global Radiation</td>
<td>W/m²</td>
</tr>
<tr>
<td>Photometer</td>
<td>Licor</td>
<td>210-LS</td>
<td>Global Illuminance</td>
<td>Klux</td>
</tr>
<tr>
<td>Weather Station</td>
<td>Vaisala</td>
<td>WXT 520</td>
<td>Air Temperature</td>
<td>°C</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Relative Humidity</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Atmospheric Pressure</td>
<td>mbar</td>
</tr>
<tr>
<td>Data Acquisition System</td>
<td>Campbell</td>
<td>CR-1000</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

To implement the Module of Experimentation, HOBO U12 data recorders were used which measure the temperature and relative humidity and to them was connected a sensitive to temperature test tube that was placed on the insides of the inner wall of the envelope.

Figure 2: Sensitive to temperature test tube on the inner wall of the envelope

The HOBO data recorder was located at the centre of space both horizontally and vertically, suspended by a fixed wire to the internal posts. The intention is to avoid contact with the constructive elements in order to prevent errors in records.

In both instruments, measurements were taken every minute for 24 hours a day. Initially, readings of every minute of both external as internal variables were taken.
We know that through the various layers of insulation it is possible to mitigate the effects of radiation and prevent internal overheating. Using the measurements obtained from both platforms, data was processed and the following results were reached.

Data Analysis

This section presents the correlations found when evaluating the different measurements. We analyse the conditions on both a cloudy and a clear day.

Cloudy Day

Taking into account the period in which data for this study was obtained, it was established that March 28 had an increase in cloudy conditions as presented in the graph of Global Radiation for that day.

In Figure 4, we see the behavior of the Global Radiation during the day. The peaks observed are due both to the presence of clouds and aerosols in the atmosphere.
We correlated the records of Global Radiation with the ones of the Temperature of the test tube, obtaining the following.

In Figure 5, we see that the correlation between the temperature of the test tube and the Global Radiation is very low (0.4146), it is noteworthy that only Global Radiation data was taken from sunrise until solar noon. This was done with the intention that subsequent records at noon do not interfere with the correlation of the temperature, since it logically continues until radiation typically tends of all. This allows us to say that on a cloudy day, radiation is not decisive for the temperature of the innerface of the envelope.
ANALYSIS OF THE THERMAL BEHAVIOR OF THE DOUBLE SKIN ENVELOPE IN THE FULL SCALE TESTING MODULES

Figure 5: Correlation between the Temperature of the test tube and Global Radiation

In Figure 6, we correlate the records of temperature in the interior of the module, with the ones of the temperature of the test tube; our dependent variable was the temperature of the test tube, which was the temperature of the innerface of the envelope. The independent variable was the temperature inside the Module of Experimentation. The correlation between these two variables was (0.956), indicating that a high percentage depends the wall interior temperature of the temperature inside the module. With this, we can establish that the insulation placed on the facade was serving its purpose, avoiding over heating of the module due to direct radiation on its southern side during a cloudy day.
Using the model established on Figures 5 and 6, we obtained the Mean Square Error, a series of data were run and compared with records obtained. The results obtained between the recorded and modelled data are listed in the following table.

Table 2: Correlations and mean square error on a cloudy day

<table>
<thead>
<tr>
<th>Test tube temperature</th>
<th>Inner temperature</th>
<th>Test tube temperature</th>
<th>Solar Radiation</th>
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<td>R.E.M.C.</td>
<td>R^2</td>
<td>R.E.M.C.</td>
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<td>0.956</td>
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<td></td>
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<td>Full Day</td>
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<tr>
<td></td>
<td></td>
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<td>16.76%</td>
</tr>
<tr>
<td></td>
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<td>Half Day</td>
</tr>
</tbody>
</table>

**Clear Day**

We analyse the records of the study period, we took March 30 as a clear day since when plotting the Global Radiation curve it appeared more stable.

In Figure 7, we can see that the behavior of the global radiation during the day was stable, even with variations that can be seen during midday we consider this as a clear day.
ANALYSIS OF THE THERMAL BEHAVIOR OF THE DOUBLE SKIN ENVELOPE IN THE FULL SCALE TESTING MODULES

Figure 7: Global Radiation on March 30

We correlated the records of Global Radiation with temperature of the test tube ones, obtaining the following for a clear day.

In Figure 8, the correlation between the values of the test tube temperature and Global Radiation during sunrise until midday is shown. And the established correlation (0.9107) allows us to infer that under these conditions the temperature of the envelope depends largely on the Global Radiation.

Figure 8: Correlation between test tube Temperature and Global Radiation
In Figure 9, we correlated the temperature inside the Experimentation Modules with Global Radiation from dawn until noon. The observed correlation (0.9402) states that dependency that presents the inner temperature with the Global Radiation that receives each of the modules.

![Correlation between Inner Temperature and Global Radiation](image1)

Figure 9: Correlation between Inner Temperature and Global Radiation

Figure 10, allows us to see the correlation (0.9677) between the temperature of the test tube and the temperature inside the module. With these results we can infer that under these conditions, the temperature inside the envelope depends more on the internal temperature of the module, rather than the global radiation received.

![Correlation between the test tube and Inner Temperature](image2)

Figure 10: Correlation between the test tube and Inner Temperature
In Table 3, using models that are shown on Figures 8 and 10, we established the Mean Square Error for each of the correlations. We can see that, still strong dependence on the temperature of the test tube with respect to the Global Radiation is greater this with respect to the internal temperature of the module, establishing this correlation as the most successful to model estimated temperatures of the envelope during a clear day.

<table>
<thead>
<tr>
<th>Table 3: Correlations and mean square error for a clear day</th>
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<td>Test tube temperature</td>
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<td>$R^2$</td>
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<td>Clear Day</td>
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**Conclusion**

For a cloudy day, the temperature of the inner face of the envelope is defined by the air temperature inside the module. The correlation that presents the Global Radiation with the test tube temperature located in the envelope is very low. During a clear day we can appreciate certain dependence of temperature of the test tube with respect to Global Radiation. Finally, under clear sky conditions, it depends on the inner temperature of the envelope. Through the model equation obtained with the graphics we saw the relationship between the various factors and scenarios.

It is noteworthy that we consider necessary that the Long Wave Radiation will be the subject to an other phase of study, analyzing the effect and impact on the thermal behavior of the envelope.

It is important to note that this document represents the first stage of experimentation, in order to obtain and determine the thermal stability of experimental modules, as mentioned in Section 2. This research is ongoing and results will be reported as well.
Acknowledgement

This project was founded by CONACYT National Council of Science and Technology of Mexico and The National Autonomous University of Mexico (UNAM). We also would like to thank to the Master and Ph.D. Program in Architecture, and the Environmental Interaction Laboratory (LIM) which facilitate the use of the building and equipment to carry out this investigation.

References


ABSTRACT

Strength and complexity of algae cell wall structures provide difficulty for microbial substrate digestion. Therefore, pre-treatment is required to break the algae cell wall. There are several types of algae cell wall pre-treatment before degradation process. Among these methods, freeze drying method is able to breakdown algae cell walls and preserve algae cell constituents simultaneously. Freeze dried (non-thermal pre-treatment) Chlorella vulgaris microalgae biomass was used as microbial substrate consumption in double chamber Microbial Fuel Cell (MFC) to generate bioelectricity. As a result, the treatment efficiency obtained in terms of Chemical Oxygen Demand (COD) removal efficiency is 63.5%. Based on the power curve obtained, the maximum power density is 8.94 mW/m² using 2.5 g/L of substrate concentration. At substrate concentration of 5.0 g/L, the MFC has COD removal efficiency of 52.38% and maximum power density of 2.87 mW/m². At the
substrate concentration of 1.0 g/L, the MFC has COD removal efficiency is 86.8%, and maximum power density of 0.11 mW/m². MFC with different freeze dried algae substrate of 1.0 g/L, 2.5 g/L and 5.0 g/L has Coulombic efficiency (CE) of 1.56 %, 18.6% and 13.1%, respectively. These results reveal that the use of freeze dried microalgae biomass could be a promising candidate in the application of MFC.

Keywords: freeze dry algae; microbial fuel cell; biomaterials; energy storage and conversion.

Introduction

The concerns of greenhouse gases emission and limited sources of fossil fuel has encouraged researchers to find alternative energy [1]–[3]. There are many types of alternative energy founded such as solar cell, hydropower, and wind power. Another alternative energy invented based on the conversion of chemical energy to electrical energy by using a special electrochemical device which is called the fuel cell [4]. There are many types of fuel cells invented, and one of the fuel cell is designed to convert waste or organic matter into energy is called Microbial Fuel Cell (MFC). MFC is an unique device compare to other fuel cell because of its anodic solutions are wastewater which is contains microbes that are responsible for digestion of substrate to produce electrons which are used for energy as bioelectricity [5], [6].

Many kind of substrates have been used for investigation of bioelectricity production by using MFC. Dry algae biomass is able to produce highest maximum power density compare to other substrates due to its high carbon sources from its lipid content. However, the bacterial digestion of algae biomass is not simple due to algal strong and complex cell wall structure which is a hindrance for microbial digestion [7]. Therefore, an algae biomass extraction is needed to break the cell wall structure to facilitate the digestion process. Some MFC research using various kinds of extraction methods before used [7]–[9]. Freeze drying is common used for dewatering microalgal biomass [10]. Freeze drying preserving cell constituents without destroying its cell wall. In this work, freeze dried Chlorella vulgaris (algae) biomass is applied to generate bioelectricity by using double chamber MFC.

Methodology

MFC Construction and Design

The MFC reactor was designed and fabricated from acrylic material. It has two chambers, each one volume is 500 ml, and labelled as the anode and cathode, respectively. Both compartments were separated by pre-treated proton exchange membrane (PEM, Nafion 117, l = 7 cm, w = 5 cm). The electrodes were made of
stainless steel mesh (l = 10 cm, w = 4 cm), coated with conductive carbon paint (SPI Paint). The cathode chamber was filled with a 50 mM phosphate buffer medium and air flow by an air pump (1000 cc per minute). The electrodes were connected to a digital multimeter (UT803, Uni-Trend Technology Ltd. China) which is connected to computer with data logger software installed (Figure 1).

![Image of MFC setup](image)

**Figure 1: A schematic diagram of freeze dry algae biomass MFC**

**Preparation and Pre-acclimation**
The closed anode chamber was inoculated by pumped in the raw sludge wastewater sample (taken from UiTM wastewater treatment plant). The working volume was used is about 400 ml. The cathode chamber was filled with 50 mM phosphate buffer medium (PBS), consisting of 4.576 g Na₂HPO₄, 2.452 g NaH₂PO₄, 0.31 g NH₄Cl, and 0.13 g KCl. After 3 days of inoculation, the wastewater was replaced with mixture of wastewater (10 ml) and freeze-dried Chlorella Vulgaris biomass powder. The optimization of MFC was investigated by manipulating three different concentrations (2.5 g/L, 5.0 g/L, and 1.0 g/L, Algaetech International Sdn. Bhd.) mixed with 50 mM PBS, and changing it by every two weeks approximately. Microalgal biomass was extracted by bead-milling method and dewatering by using freeze dry method.

**Data Collection and Analysis**
The digital multimeter was connected to computer with installed data logger software (UT803, Uni-Trend Technology Ltd. China). After a stable voltage generation was occurred, a variable resistor was applied to the system (0.5 Ω to 10 M Ω) to determine its polarization curve. Current was calculated by using Ohm’s Law, \( I = \frac{E_{cell}}{R_{ext}} \) where \( E_{cell} \) is cell voltage generated for each load, \( I \) is the current.
for each load, and \( R \) is the external load resistor which is applied. Power generation curve was determined by using \( P = \frac{I}{E_{\text{cell}}} \), where \( P \) is power generated for each load, \( I \) is the current for each load and \( E_{\text{cell}} \) is the cell voltage for each load.

Some samples were taken for each initial and final of MFC operation to determine its chemical oxygen demand (COD), in mg . L \(^{-1} \), by using reactor digestion method (High Range, 20-1500 mg/l, HACH). The result of COD removal percentage is useful to calculate Coulombic efficiency (CE), as feed batch system (Equation 1).

\[
CE = \frac{8 \int_{0}^{t} I \, dt}{F V_{\text{an}} \Delta \text{COD}}
\]

Where \( \Delta \text{COD} \) is change of COD concentration (mg/L), \( I \) is current (A), \( t \) is change in time (s), \( V_{\text{an}} \) is working volume (volume liquid in anode compartment, L), \( F \) is Faraday’s constant (96,500 C/mol e\(^{-}\)), and \( 8 \) is a constant in (1), based on \( \text{MO}_2 = 32 \) for the molecular weight of oxygen and \( b = 4 \) for the number of electron transferred per mole of oxygen.

Result and Discussion

Effect of Different Concentrations of Freeze Dried Algae Biomass Feedstock

Three different substrates (freeze dried algae biomass) concentration is applied to MFC. From the three different polarization power curves (Figure 2), the power curve produces the highest maximum power point is 8.94 mW/m\(^2\) at 2.5 g/L of concentration of freeze dried algae biomass. 5.0 g/L of freeze dried algae biomass concentration produces power curve with maximum power point of 2.87 mW/m\(^2\) while 1.0 g/L of freeze dried algae biomass concentration produces 0.11 mW/m\(^2\). In this case, different concentration has an effect on the power production. 2.5 g/L substrate concentration produce more power than 1 g/L substrate concentration. Therefore, the more concentration of substrate is applied, more power is produced by MFC [8].

The concentration freeze dried algae biomass of 5.0 g/L produces low power density compare to 2.5 g/L, maybe due to many reasons such as the anode, cathode, chemical species in electrolyte, proton exchange membrane (PEM), application of microbes species, the configurations of fuel cell and the condition of the operation [11].
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Chemical Oxygen Demand (COD) Removal and Coulombic Efficiency

COD of MFC operation is taken to determine its percentage removal of organic matter in water. Three different substrate (freeze dried algae biomass) concentrations is applied to MFC (Figure. 3). The percentage of COD removal at 1 g/L of substrate concentration is 86.8 %, 2.5 g/L shows 63.5 % and 5.0 g/L shows 52.38 %. The differences of COD between the initial and final of MFC operation determines the coulombic efficiency (CE). At 1.0 g/L of substrate concentration, CE result is about 1.56 %. At 2.5 g/L, the CE result is 18.6 % while 5.0 g/L only produce CE about 13.1 %. These results show that MFC is not only able to generate power but it able treat wastewater and increase the quality of water, as well.

From the data (Figure. 3.), 1 g/L has the highest COD removal but lowest CE while 2.5 g/L has the highest CE but lower than 1 g/L. 5 g/L has lowest COD removal but higher CE than 1 g/L and a little bit lower than 2.5 g/L. From these differences, low COD removal has relatively high CE, significantly shown between 1 g/L and 2 g/L. There is a little differences between 2.5 g/L and 5 g/L (CE in range of 15-20%). Velasquez-Orta et al. [8] shows that the relationship between COD removal and CE shows that the CE is high (28 % for C. Vulgaris and 23 % for U. Lactuca) at range of low COD removal (range of 100 to 500 g/L) and reached 10 % plateau and decrease of CE beyond 600 mg/L of substrate concentrations. Consequently, the more substrate concentrations produce the higher COD removal efficiency but CE reaches plateau and decreases.
decrease of COD removal at low power generation is probably due to large size of organic matter for fermentation, aerobic respiration and bacterial growth [9].

![Graph showing COD removal and coulombic efficiency](image)

Figure 3: The percentage of chemical oxygen demand (COD) removal and coulombic efficiency in response to different substrate concentration.

**Conclusion**

Bioelectricity production from a freeze dry pre-treated microalgae, *Chlorella vulgaris* examined in a double chamber Microbial Fuel Cell (MFC). Freeze dry pre-treated *C. vulgaris* is a common pre-treatment method due to its high lipid recovery by preserving the algal cell constituents. As a result, the maximum power density is 8.94 mW/m² and COD removal efficiency of 63.5% with 2.5 g/L of substrate concentration. MFC with freeze dried algae substrate of 1.0 g/L, 2.5 g/L and 5.0 g/L has coulombic efficiency of 1.56%, 18.6% and 13.1%, respectively. Therefore, the bacterial substrate consumption of freeze dry pre-treated *Chlorella vulgaris* algae biomass able to produce bioelectricity in MFC.

**Acknowledgement**

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References


Mode III Stress Intensity Factors of Sickle-Shaped Surface Cracks in Round Bars

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ABSTRACT

The solutions of stress intensity factors (SIFs) of sickle-shaped surface crack in round bars are not currently available especially when the cracks are subjected to mode III loading. Mode I SIFs can be obtained in open literature however they are also insufficiently completed. Therefore, this paper develops numerically the sickle-shaped crack in round bars using ANSYS finite element program. In order to validate the model, the existing mode I SIFs are used and then compared with the present model. It is found that both models are well agreed with each other. There are two important parameters used such as the crack aspect ratio, a/b and the relative crack depth, a/D ranging between 0.2-1.2 and 0.1-0.6, respectively. SIFs based on J-integral are calculated along the crack fronts for various crack geometries. It is found that the SIFs are significantly affected by a/b and a/D. For the relatively straight-fronted crack (a/b ≤ 0.2), the SIFs are almost flattened along the crack front. When a/b increased (a/b > 0.2), the SIFs have decreased whereas they are increased when a/D increased. It is also found that the SIFs closed to the outer edge are higher than the SIFs at the deepest crack along the crack front. However when a/b > 1.2, the role of SIFs along the crack fronts are inversed where lower SIFs are observed at the outer point compared with the middle point.

Keywords: sickle-shape crack; mode III loading; surface crack; round bar.

Introduction

Shafts in the form of various geometries and shapes are frequently used to transmit power from one point to another. Under certain circumstances, the shafts are exposed to external elements such as corrosion leading to the formation of surface cracks. According to [1], arbitrary initial shape of surface crack grew to take a
semi-elliptical shape. The solutions of SIFs for semi-elliptical crack shapes can be found in [2-4]. However under special conditions, the arbitrary shaped-crack grew to have a sickle-shaped surface cracks. The solutions of SIFs of sickle-shaped cracks can be found in [5-6]. However, the SIFs under mode III loading are not available in open literature.

The sickle-shaped surface cracks occur circumferentially around the solid bar. The fractographic observation can be found in [7]. It is indicated the crack formed around the bolt and propagated into the bar. Once, the crack driving force approached the critical value the bolt experienced the final failure. The finite element analysis on the sickle-shaped crack is documented by Mattheck et al. [7]. However, due to the computational disadvantages, the SIFs of such crack are limited. Based on the comparison between the normalized SIFs among other works, there are huge discrepancies between the results.

Then, Hobbs et al. [8] experimentally conducted using a photoelastic approach on the sickle-shaped cracks. They have concluded that the shape of the crack front does not have a significant effect on the SIFs especially the maximum SIF at the middle of the crack front. However, it does influence the distribution around the crack front. Carpinteri et al. [9] investigated the SIFs of sickle-shaped crack subjected to complex mode I loading. On the other hand, Carpinteri et al. [6] extended their work to study the sickle-shaped crack under eccentric axial loading.

Therefore, this paper presents the solutions of SIFs of sickle-shaped surface cracks in round bars under mode III loading. There are two important parameters that are investigated such as crack aspect ratio, a/b ranging in between 0.2 to 1.2 and relative crack depth, a/D in between 0.1 and 0.6. ANSYS finite element program is used to model and solve the crack problems. The SIFs are then calculated along the crack front of various crack geometries.

**Methodology**

**Sickle-Shaped Cracks**

Due to the symmetrical effect only a quarter finite element model is used where the radius, R = 25 mm and the half length of the solid round bar is 200 mm. Figure 1 shows the cross-sectional area of sickle-shaped surface crack where O and O' are the central point of circle and semi-ellipse, respectively. The sickle-shaped crack front is based on the semi-elliptic centered at O'. There are seven values of crack aspect or semi-elliptical ratios, a\textsubscript{minor}/b\textsubscript{major} used ranging between 0.0 to 1.2 with an increment of 0.2. While, six relative crack depth, a/D are used namely 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6. All of these are used in order to study the influence of different relative crack depths and crack aspect ratios on the stress intensity factors. The SIFs are determined at six different locations along the crack front and the SIF at the point C is not determined due to the singularity problems. It is estimated that the nearest point to point C is 83% measured from point A. The location of each point along the crack front is also normalized such as x/h for the location of point P.
Finite Element Modelling

The construction of finite element model is started with the model of cross-sectional area as shown in Figure 2. Once it is completed, the model is extruded along the y-axis with a length of 200 mm. It is selected to ensure the effect of torsion or tension loading is sufficient enough and thus not affecting the stress distribution around the crack region. The extruded volume model is presented in Figure 2(a). Special attention is given at the tip of the sickle-shaped crack where three-dimensional 20-node solid element (SOLID186) is used. The square-root singularity of stresses
and strains around the crack tip is modelled by shifting the mid-point nodes to the quarter-point location close to the tip. Firstly, the two-dimensional model is meshed and then it is swept along the crack front. Then, the remaining model is meshed with irregular similar element. The quarter finite element model is shown in Figure 2(b) with its corresponding crack tip singular element.

In order to remotely apply the bending moment to the model, an independent node is created about 50 mm ahead of bar ends where it is modelled with target element (TARGE170) while the element at the edge of the bar is modelled with node-to-surface contact element (CONTA175). Then, it is required that the whole solid round bar to follow any mechanical movement by the independent node. Then, both the independent node and the nodes at the surface edge of the bar are connected using multiple constraint element (M PC184) as shown in Figure 3. Then, the follower load element (FOLLW201) is used in order to ensure any mechanical displacement occurred at the pilot node to be followed by the solid round bar. On the other hand, the whole edge surface is symmetrically constrained except the crack faces. The left surface plane is also symmetrically constrained. The bending moment is applied to the independent node.

The stress intensity factors (SIF) along the sickle-shape crack front are determined using ANSYS finite element program. The determination of SIFs is based on the $J$-integral where it can be directly converted into SIFs using Eq. (1) as long as the problem within the elastic ranges and has fulfilled the plain strain condition:

$$K_1 = \frac{\sqrt{J_i E}}{1-v^2}$$

Figure 3: The boundary conditions and the loading on the finite element model

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MODE III STRESS INTENSITY FACTORS OF SICKLE-SHAPED SURFACE CRACKS IN ROUND BARS

Where, $K_i$ is a SIF of mode $i = I$ and $III$, $J$ is a $J$-integral determined directly from program, $E$ is a modulus of elasticity and $v$ is a Poisson’s ratio. In order to generalize the SIFs, it is recommended to convert them into a normalized value called a dimensionless mode I SIF or geometrical correction factor under axial stress, $F_{I,a}$ as Eq. (2):

$$F_{I,a} = \frac{K_{I,a}}{\sigma_a \sqrt{\pi a}}$$

Where, $\sigma_a$ is an applied bending stress, $K_{I,a}$ is a SIF under axial stress and $a$ is a crack depth. Before the model is further used, it is compulsory to validate the present model with the existing results of similar finite element model [5]. According to Figure 4, it is revealed that the present model is well agreed with the existing model. Therefore, this present model can be utilized for the further analysis. The model in Figure 3 is only suitable for mode I loading and it cannot be used for mode III loading. Then, it is constructed in full model as shown in Figure 5. At one end, the bar is fully fixed in all degree of freedom while at another end the torsion moment, $T$ is applied at the independent node in order to twist the bar. The dimensionless mode III is normalized according to Eq. (3):

$$F_{III} = \frac{K_{III}}{\tau \sqrt{\pi a}}$$

Where, $\tau$ is an applied shear stress, $K_{III}$ is a SIF under shear stress and $a$ is a crack depth.

![Figure 4: Model validations of the present and the existing models](image-url)
Results and Discussion

In this paper, the discussion is divided into three categories based on the effect of relative crack depth, $a/D$, crack aspect ratio, $a/b$ on the SIFs along the crack front and the SIFs at the deepest point ($x/h = 0.0$) along the crack front. Only selected cases of SIFs are discussed since their behaviour are similar but different in magnitudes. The other values of SIFs are tabulated in Table 1.

![Figure 5: Full finite element model of sickle-shaped surface crack](image)

**Effect of Relative Crack Depth on the SIFs**

Relative crack depth, $a/D = 0.4, 0.5$ and $0.6$ are presented and discussed. Other values of $a/D$ are not presented since the pattern or behaviour of stress intensity factors are almost similar but different in magnitudes. Figure 6 shows the role of relative crack depth on the SIFs along the crack fronts of various crack geometries. It is revealed that the distributions of SIFs are almost similar except when $a/D$ increased, the SIFs are also increased. This behaviour is similar with mode I SIFs as reported in [2]. It is obvious since increasing $a/D$ on the other hand reduced the cross-sectional area of the ligament and therefore increasing the SIFs. The reduction of crack ligament increased the shear stress and therefore affecting the SIFs. Under mode I, for the relatively straight-fronted cracks ($a/b \leq 0.2$), the SIFs along the crack fronts are almost flattened. However under mode III, the role of SIFs are different where the SIFs closed to the outer edge are always higher that the SIFs at the middle point ($x/h = 0.0$). This is due to the fact that at the outer point, the material is easily deformed when compared with the location in the middle along the crack front. Similar SIFs behaviour are observed for other $a/b$. Once $a/b \geq 1.2$, the SIFs along the crack fronts have changed where the SIFs at $x/h = 0.0$ is slightly
higher that the SIFs at the outer point. It is indicated that once the shape of crack equal to $a/b = 1.2$, the crack growth along the crack front grow in a similar rate and it is initiated at the point $x/h = 0.0$. Whereas for other values of $a/b$, the crack firstly initiated at the area closed to the outer surface.

**Effect of Crack Aspect Ratio on the SIFs**

Figure 7 reveals the effect of crack aspect ratio, $a/b$ on the SIFs when the relative crack depth, $a/D$ is varied. In this discussion, $a/b = 0.6, 0.8$ and $1.2$ are selected since the role of SIFs along the crack fronts are almost similar except in the magnitude. Figure 7(a) shows the SIFs along the crack front for $a/b = 0.6$ when $a/D$ is varied. It is clearly observed that for the cracks, $a/b \leq 0.4$, the role of SIFs along the crack front is insignificant where changing the crack depth is not greatly affected the SIFs. Similar works on SIFs can be obtained from [2, 3]. The SIFs around the outer surface are slightly higher for higher $a/D$. Similar SIFs behaviour is observed for $a/b = 0.8$. However the curves of SIFs are flattened. It is indicated that when higher $a/b$ is used, the SIFs around the outer edge are lowered when compared with the SIFs at $x/h = 0.0$. If $a/b = 1.2$ is used, higher SIFs occurred at $x/h = 0.0$. This is due to the fact that when $a/b = 1.2$, the crack formed circumferentially around the cylindrical bar with the maximum crack depth occurred at $x/h = 0.0$. On the other hand, this location also experienced higher shear stress with other points and therefore producing higher SIFs.

**SIFs at the Deepest Crack ($x/h = 0.0$)**

In order to comprehensively understand the SIFs when $a/b$ is varied, it is important to represent the role of SIFs at $x/h = 0.0$ when $a/D$ is increased. This location is important since it is the deepest point along the crack front and also determined the detrimental effect compared with other positions. Figure 8 reveals the SIFs at the deepest point ($x/h = 0.0$) when $a/b$ is varied. It is indicated that the SIFs are significantly dependent on $a/D$. For $a/b \leq 0.4$, the SIFs are lowered when $a/D$ increased. This is due to the fact that for the relatively straight-fronted crack, higher SIFs occurred at the outer edge and lower SIFs values at the middle point. When higher $a/b$ is used for example $a/b \geq 1.0$, the crack formed circumferentially around the bar and the deepest point occurred at $x/h = 0.0$ and therefore increasing the SIFs. Different behaviour of SIFs are observed for mode I loading [3, 5, 6] where the SIFs at $x/h = 0.0$ are increased as $a/D$ increased. This is due to the different crack opening mechanisms where under mode I loading, the crack faces are always opened across the crack front.
Figure 6: The effect of relative crack depth, $a/D$ on the SIFs when crack aspect ratio, $a/b$ is varied, (a) $a/D = 0.4$, (b) $a/D = 0.5$ and (c) $a/D = 0.6$
Figure 7: The effect of crack aspect ratio, $a/b$ on the SIFs when crack aspect ratio, $a/b$ is varied, (a) $a/b = 0.6$, (b) $a/b = 0.8$ and (c) $a/b = 1.2$
Table 1: List of SIFs of sickle-shaped crack under torsion moments.

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Conclusion

In this paper, sickle-shaped surface crack in round bars are modelled numerically using ANSYS finite element program. Two important parameters are used such as crack aspect ratio, $a/b$ and relative crack depth, $a/D$ and the stress intensity factors are calculated along the crack front, $x/h$. The model is then subjected to mode III loading from which the following conclusions can be drawn:

1. The SIFs around the outer surface are relatively higher than the SIFs at the middle point. However when $a/b > 1.0$, the maximum SIFs are observed to occur at the middle instead of outer points which is attributed to the change of crack geometries.
2. For the crack geometries of $a/b < 1.0$, the distributions of SIFs are strongly related to the crack front where the SIFs increased at the points closer to the outer surfaces.
3. For the crack geometries of $a/b \geq 1.0$, the maximum SIFs occurred at the deepest points and they decreased along the crack front as it approached the outer points.
References


Perpendicular Dowel-bearing Strength Properties without Glue Line for Mengkulang Species

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ABSTRACT

The aim of this project is to generate connection data that can be employed in the design of connections for Malaysian timber species particularly for glulam products. This investigation focuses on evaluating dowel-bearing strength for timber-based products. Thus far, limited studies on dowel-bearing strength were published and reported. Mengkulang, (Heritiera spp), was used to evaluate the dowel-bearing strength properties. Two bolt diameters 16 and 20mm consecutively were selected in this study. The project comprised experimental work that was based ASTM D5764, using half-hole testing setup. The dowel-bearing strength, $F_e$ for 16mm and 20mm diameter were determined from 5% diameter offset yield load method. Through the experimental work and analysis, the percentage difference between 16mm and 20mm was found 15% increased from 16.24N/mm$^2$ to 19.21N/mm$^2$, respectively. The dowel-bearing strength increased when the dowel diameter increased. The comparison between dowel-bearing strength of 5% diameter offset load, $F_e$ and maximum load, $F_h$ of glulam without glue line has successfully analysed. The $F_e$ and $F_h$ was found 16.24 N/mm$^2$ and 18.50N/mm$^2$ for the 16 mm diameter while was 19.21N/mm$^2$ and 22.69 N/mm$^2$ for the 20mm diameter respectively.

Keywords: timber; glulam; mengkulang; glue line; dowel-bearing strength
Introduction

Dowel-bearing strength also referred to as embedment strength of timber. It is one of the properties that is used to estimate the lateral connection of wood design strength performance to fastener bending strength. The embedment strength has relations to the glulam wood features such are wood species, thickness, moisture content, specific gravity, wood grain direction and presence of glue line. Glue line is a bonding between one or more thickness of wood surface to another using wood adhesive.

Dowel-bearing strength was additionally presence focus for the building timber materials, for example, laminated veneer timber, plastic wood composite and glue laminated. There are very limited studies on experimental work especially for structural size timber and connection system. According to Hassan et al., [1], dowel-bearing strength is one of an essential parameter in determination of European Yield Model (EYM) and it influences the design value capacity, Z of the bolts. Most available published data for dowel-bearing strength of the Malaysian tropical timber is for solid timber that has been investigated using Kempas species using Spring Theory method. This method tested for wood dowel compressed with steel block and wood block compressed by steel dowel [2]. Dowel-bearing strength of two species from Guatemalan hardwood in parallel to grain direction is found reported by Rammer [3].

In order to promote the application of glulam in Malaysia on the timber connection, this study is conducted to determine the dowel-bearing strength properties of glulam without glue line (lamination thickness) made of Mengkulang species on the effect of two (2) different bolt diameter sizes that are 16mm and 20mm.

Material and Method

In order to perform the dowel-bearing strength test, this study tested using half-hole test method according to ASTM-D5764-97a and BS EN 383:1993. This method allows full exposure of the specimens during testing. The details on the specimens during the test such as appearance of cracks or any failure patterns were observed. The important physical properties of Mengkulang specimen has been observed and recorded.

The specimen dimension for 16 mm bolt diameter is 64 mm × 64 mm × 38mm and 20 mm bolt diameter is 80 mm × 80 mm × 40 mm. Figure 1 shows the specimen hole free from glue line.
Dowel-bearing strength set up comprised of a rectangular wooden block with half-hole set on the uniform base on UTM and a steel load head pushed to the dowel that placed in the half-hole on the specimen. The tests were run on a UTM with 97.8 kN limit load cell.

A steady displacement rate of 1 mm/min or 0.02 mm/s was utilized and the tests were run until the load head touches the sample or when the displacements load remain consistent [4]. Figure 2 shows the dowel-bearing strength test set up.

Dowel-bearing strength properties are resolved from 5% offset load as shown in Figure 3. The methodology was started with the dowel has been placed into the dowel hole. Then, the specimen has allocated in the testing machine where its easier for compressive load uniformly applied along dowel length. The dowel and moveable crosshead were used to prevent bending of dowel during loading. The
failure specimen was configured by dowel-bearing strength test perpendicularly. Next, the load has been selected at which the offset line meets the load displacement curve. The greatest intersect load should be utilized as the 5% offset load if the offset line does not meet the load-displacement curve.

Figure 3: Load definition obtained from load-displacement curve (ASTM-5764-97a, 2013)

As indicated by ASTM-D5764-97a:2013, the Equation 1 shows calculation for dowel-bearing strength, $F_e$ which comprised 5% diameter offset load, $F_{5\%}$.

$$F_e = \frac{F_{5\%}}{d \cdot T}$$  \hspace{1cm} (1)

If the offset line does not meet the load displacement curve, Equation 2 is used to compute the dowel-bearing strength, $F_e$ which consisted of maximum load, $F_{\text{max}}$.

$$F_e = \frac{F_{\text{max}}}{d \cdot T}$$  \hspace{1cm} (2)

Where $F_{5\%}$ is 5% diameter offset load obtained from the test, $F_{\text{max}}$ is the maximum load collected from the test, d is a bolt/dowel diameter and T is the thickness of dowel-bearing samples. Equation 3 shall be computed for determination of the dowel-bearing strength ($F_h$), according to BS EN 383:1993 [5].

$$F_h = \frac{F_{\text{max}}}{d \cdot T}$$ \hspace{1cm} (3)
Result and Discussion

Dowel-bearing Strength, $F_e$, Properties For Without Glue Line of Mengkulang Species using 16 mm Dowel Diameter.

Figure 4 shows load versus displacement in determining 5% offset load for 16 mm dowel diameter. Figure 5 shows of 5% diameter offset load for the minimum, mean and maximum of the load.

![Figure 4: Load versus displacement for 16 mm dowel diameter](image)

Figure 5 shows one result of the 5% diameter offset load is outliers and disposed of 23 remaining samples. The mean value for 5% diameter offset load was 9.83 kN and standard deviation and the coefficient of variance were 0.56 and 13%, accordingly.

![Figure 5: F5% diameter offset load test result for dowel-bearing strength without glue line specimens using 16mm dowel diameter](image)
Figure 5 shows one result of the 5% diameter offset load is outliers and disposed of with 23 remaining samples. The mean value for 5% diameter offset load was 9.83 kN and standard deviation and the coefficient of variance were 0.56 and 13%, accordingly.

Figure 6 shows the distribution of dowel-bearing strength values. The $F_e$ was 16.24 N/mm² and standard deviation was 0.80 and the coefficient of variance was 4.93%.

For computation of moisture content and density, the mean estimation of moisture content and density for samples was 13.75% and 650.06 kg/m³, individually. Figure 7 demonstrates the regular state of samples after an optimum load was applied to samples without glue line using 16 mm dowel diameter.
As a summary, the 16 mm dowel diameter without glue line given value for mean 5% diameter offset load, \( F_{5\%} \) was 9.83 kN while for the mean dowel-bearing strength, \( F_e \) was 16.24 kN and the value for coefficient of variance was 4.93%.

**Dowel-Bearing Strength, \( F_e \) Properties for Without Glue Line of Mengkulang Species using 20 mm Dowel Diameter**

Figure 8 shows load versus displacement in determining 5% offset load for 20 mm dowel diameter. Figure 9 shows 5% diameter offset load for the minimum, mean and maximum of the load.

Figure 8: Load versus displacement for 20 mm dowel diameter

Figure 9: \( F_{5\%} \) diameter offset load test result for dowel-bearing strength without...
glue line samples using 20 mm dowel diameter

Figure 9 shows $F_{5\%}$ diameter offset load remaining 21 samples with few outliers disposed. The mean value for 5% diameter offset load was 15.36 kN and standard deviation was 1.56 while the coefficient of variance was 19%. Figure 10 similarly shows the distribution of dowel-bearing strength for the minimum, mean and maximum value.

![Figure 10](image)

**Figure 10: Dowel-bearing strength result for dowel-bearing strength without glue line samples using 20 mm dowel diameter**

Figure 10 shows the dowel-bearing strength for the remaining 21 samples $F_e$ with few disposed outliers. The mean value for dowel-bearing strength, $F_e$, was 19.21 N/mm$^2$ although the standard deviation and coefficient of variance were 1.95 and 10.15%, accordingly. For computation of moisture content and density, the mean estimation of moisture content and density for samples were 9.56% and 772.50 kg/m$^3$, respectively. Figure 11 demonstrates the regular state of typical crack after an optimum load was applied using 20 mm dowel diameter.
As a summary, the 20 mm dowel diameter without glue line given value for mean 5% diameter offset load, $F_{5\%}$, was 15.36 kN while for the mean dowel-bearing strength, $F_e$, was 19.21 kN and the value for coefficient of variance was 10.15%.

**Dowel-bearing Strength, ($F_e$ and $F_h$) of Glulam to the Different Dowel Diameter for Without Glue Line**

Table 1 demonstrated the percentage differences of dowel-bearing strength between 5% diameter offset load, $F_e$, and maximum load, $F_h$, of glulam for without glue line samples. Figure 12 demonstrates the dowel-bearing strength of 16 mm dowel diameter for without glue line specimens was increased 15% from 16.24 N/mm$^2$ to 9.21 N/mm$^2$ while 20 mm dowel diameter was increased 18% from 18.50 N/mm$^2$ to 22.69 N/mm$^2$.

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It is shown that 16 mm for $F_e$ and $F_h$ produced lower dowel-bearing strength value compared to 20 mm. This outcome demonstrates that the higher the bolt diameter, the higher the dowel-bearing strength of glulam made of Mengkulang species. The percentage difference for dowel-bearing strength in terms of pattern is discovered where all mean estimation of dowel-bearing strength increased when
the dowel diameter is increased. It demonstrates that this findings support the statement reported by Jumaat et al. claimed the dowel-bearing strength of timber was influenced by the dowel diameter [6].

**Figure 12:** The percentage differences of dowel-bearing strength, $F_e$ and $F_h$ without glue line specimens

**Comparison Between Dowel-bearing Strength ($F_e$ and $F_h$) of Glulam without Glue Line Using 5% Diameter Offset Load and Maximum Load**

The comparison between dowel-bearing strength, Fe and Fh without glue line specimens using 16 mm and 20 mm dowel diameter shown in Figure 13.

**Figure 13:** Comparison between $F_e$ and $F_h$ without glue line specimens using 16mm and 20 mm dowel diameter
In this study, no significant different were found between the dowel-bearing strength without glue line of Mengkulang samples to the results of solid timber samples that was studied with utilizing three (3) different dowel diameter which were 8, 10 and 12 mm [6]. All measurements of the sample test method were referring to BS EN 383:1993 and utilizing full-hole test technique. For conclusion, it was found that the dowel-bearing strength ($F_e$) utilizing 5% diameter offset load by ASTM-5764-97a (2013) is lower than determination of the dowel-bearing strength ($F_h$) by BS EN 383:1993.

Conclusion

The dowel-bearing strength, $F_e$ (ASTM) was determined from 5% diameter offset load method, $F_5\%$, while $F_h$ (BS EN) was determined from maximum load, $F_{max}$. The dowel bearing strength, $F_e$ of glulam for two different dowel diameters were compared. The percentage of $F_e$ and $F_h$ between 16 mm and 20 mm diameter was increased by 15% and 18% respectively. The value of 16 mm diameter was 16.24 N/mm² to 19.21 N/mm² and for 20 mm diameter was from 18.50 N/mm² to 22.69 N/mm², respectively. It was found that the dowel-bearing strength increased when the dowel diameter increased. The comparison for dowel-bearing strength of glulam without glue line which is 5% diameter offset load, $F_e$ and maximum load, $F_h$ have been analysed. The mean value for dowel-bearing strength, $F_e$ of 16 mm dowel diameter was 18.50 N/mm² while the standard deviation and coefficient of variance were 1.29 and 7%, accordingly. The mean value of dowel-bearing strength, $F_h$ for without glue line using 20 mm dowel diameter was 22.69 N/mm² while the standard deviation and the coefficient of variance were 1.63 and 7%, respectively.

Acknowledgement

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References


The Use of Edible Vertical Greenery System to Improve Thermal Performance in Tropical Climate

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ABSTRACT

The vertical greenery system (VGS) is a passive shading and urban greening solution for multi-storey buildings. Buildings installed with VGS could benefit from lower indoor air temperature, which in turn will save energy. As cities are experiencing urban heat island due to excessive development and overpopulation, building occupants turn to mechanical cooling to cool the interior space. Normally, the VGS is installed with living aesthetic plants that function to absorb solar radiation. However, in this paper, Psophocarpus Tetrogonobulus (Winged Bean Plant) is selected as the plant medium based on its ability to provide vegetable pod, have longer lifespan and withstand heat gain from long sun exposure. This edible VGS could lower the building energy cooling load and at the same time provide food production at a household level. This paper presents a series of recently measured data from the use of Test Cell (ground level) at University Sains Malaysia, Penang. The VGS managed to reduce the surface temperature by an average of 2.4°C, while the maximum surface temperature drop achieved was 6.4°C. These promising results
indicated that the VGS installed with edible plants such as wing beans could save energy through the benefits of shading in urban multi-storey buildings.

**Keywords:** vertical greenery system; multi-storey building; temperature reduction; energy saving

**Introduction**

The rising trend for migration from rural to urban areas has been observed globally as well as in Malaysia. According to the Department of Statistic Malaysia [1], at least 70 percent of 40.6 million Malaysians would populate Malaysia's major cities by 2020. As a result of this urban migration trend, landed property has become scarce and housing developers have focused in constructing multi-storey buildings for urban dwellers. Hence, when many high-density buildings are constructed, the basic requirements for vegetation have often been overlooked.

There are many manmade structures that replaced trees such as concrete pavement, buildings and street fixtures. Urban areas built with hard surfaces often experience urban heat island (UHI) effects that in turn contribute to the rising of global ambient temperature and climate change [2]. Apart from this, human activities also contributed to climate change. From the burning of fossil fuel to feed the demand of industries, transportation, businesses and comfortable living, urban dwellers are responsible towards the increase in carbon dioxide emissions [3].

The use of mechanical cooling is one of the contributor’s to rising energy consumption in cities. Urban dwellers are keen to use air conditioning system as part of cooling mechanism to cool the indoor environment. When this system operates, it increases heat gain built up towards outside ambient temperature through gas release. As stated by Zain-Ahmed [4], this system consumed at least 50 percent of overall building electricity and increased energy consumption if it is not properly controlled.

**Aim**

The aim of this paper is to investigate the optimum temperature reduction using vertical greenery system (VGS) installed with Psophocarpus Tetragonobulus (winged bean plant) on a test cell. The application of this system is tested on ground level before application on high rise building can take place.
Literature Review

Definition

Vertical greenery system (VGS) is akin to green building envelope. There are many similar keywords or phrases that are in line with the vertical greenery system such as bio-facade [5], green facade [6], green wall [7], bio-shader [8] and so on. The vertical greenery system is commonly divided into two groups which are called “support system” and “carrier system” [9,10]. The support system is normally associated with green façade while the carrier system is similar to living wall system. In this paper, the vertical greenery system is more focused towards the support system. The support system functions by guiding plants up on a vertical surface depending on types of structures, climate condition and budget. When compared with carrier system the support system is more economical and can be implemented on household level. It is considered cheap in terms of production and maintenance. However, the support system is limited to climbers and creepers.

Thermal Effects on Vertical Greenergy System (Support System)

Previous studies related with the use of vertical greenery system are more focused on the improvement of building thermal performance using ornamental plants. There are few researchers who opted to explore the use of edible plants rather than ornamental plants in tropical climate condition. This transition could produce multiple benefits that would lead to the reduction of energy consumption and some food supply for the household. In terms of thermal effect, Sunakorn and Yimprayoon [11] have conducted a research in Thailand and were able to reduce the air temperature by a maximum of 4.71°C. Moreover, they found that the VGS also improved the ventilation in a naturally ventilated room.

In Netherland, Perini [12,13] studied the differences between the thermal performance of support system that are attached directly on the wall and the indirect system (with an air gap). The results showed that the wall behind a direct VGS was able to reduce an average surface temperature of 1.2°C when compared with the surface of a bare wall. For the indirect approach, the VGS was able to reduce the surface temperature at least 2.7°C.

A similar study using indirect VGS was conducted in Penang Malaysia [14,15]. In this study, the VGS installed with edible legume plant was able to reduce the surface temperature by a maximum of 11.0°C. However, the comparison between the surface wall behind the VGS and the bare wall was not conducted side by side, which may trigger different results. Majority of the findings from thermal performance studies that uses VGS support system were conducted at the ground level. In this paper, the investigation of ground level VGS is essential before it can be compared with higher level.
Experimental Description
The research was carried out using a ground level test cell located at the University Sains Malaysia, Penang (5°21’17.1”N, 100°18’28.3”E). This test cell was chosen as a pilot study to gather preliminary results before the implementation of VGS in high rise condition. The test cell is situated on a ground level that can be compared later with multi-storey level results (Figure 1). The size of the test cell is 4.8 m (l) × 4.2 m (w) × 3.3 m (h). It is made out of brick wall and metal deck roofing. Only a portion of surface wall that expose to west orientation will be used to measure thermal evaluation. This research investigated possible surface temperature drop between a bare wall (without VGS) and wall behind the VGS (with VGS). The measurements were compared side by side simultaneously to achieve better results [16].

This research uses a rack system that is made out of plywood that housed the VGS plant. The rack system functions to guide the plant upwards to reach its desired foliage density. The size of the rack system matches the size of a single door leaf that is 900 mm (w) × 2100 mm (l). The rack system is divided into two different intervals, which are upper interval and low interval. Two different points were measured to identify different surface temperature values (Figure 2).

Figure 1: Test Cell on Ground Level
Experimental Equipment
The main parameters recorded in this research are surface temperature, ambient temperature and air velocity. The surface temperature was recorded using an IRtek laser point thermometer (Figure 3a). While the ambient temperature and air velocity was recorded using a hot wire thermo anemometer. The IRtek laser point thermometer measured at two different points (600 mm, 1500 mm from the bottom of the ground level) for each bare wall (without VGS) and VGS wall (with VGS) [17]. The readings were taken at 2 hours interval from 9 a.m to 5 p.m. The Data collection was conducted for a one week period on dry season between (13 March – 19 March 2015) [18].
Plant Selection
Psophocarpus tetragonobulus (winged bean plant) was used to investigate the surface temperature drop (Figure 4). Previous research is focused on the use of ornamental plants that only improves thermal and aesthetic purposes. The winged bean plant was chosen in this research for the benefits of improving thermal performance and also provides food for building occupants. The winged bean plant was first introduced by Fukaihah [14], who indicated that it is the most effective legume plant to be used as part of vertical greenery system. The author added that the plant could absorb heat from solar radiation more effective due to its darker leaf features when compared with other edible legume plant such as P isum sativum (Sweet Pea), Vigna unguiculata sesquipedalis (Long Bean) and Phaseolus vulgaris (Kidney Bean). A part from that, the winged bean plant has a longer lifespan due to its tuberous root that can store sufficient nutrients over a two-year period.
Results and Discussion

Temperature Evaluation
During the investigation, the winged bean plant was used as the shading component of the vertical greenery system. The temperature evaluations were conducted for a week. Data of 3 clear days were selected in order to identify and differentiate dry and wet readings. Measurements were taken from two interval points. From the experiment, the lower interval (600 mm from floor level) of wall behind VGS managed to reduce surface temperature at least an average drop of 2.4°C (Figure 5). The bare surfaced wall indicated an average reading of 31.5°C, whereas the wall behind the VGS recorded 29.1°C. The maximum surface temperature drop achieved at this lower interval was 6.4°C, which occurred on day 2 (14 March 2015) at 3 p.m. The minimum surface temperature drop was at least 0.7°C recorded on day 2 at 1 p.m. When compared with the upper interval as shown in Figure 6, the lower interval readings performed efficiently. The foliage cover at this interval was denser compared with the upper interval.
The upper interval (1500 mm from ground level) readings showed different results (Figure 6). At this level, the VGS managed to reduce the surface temperature by an average of 1.1°C. The maximum surface temperature drop recorded was 4.4°C that occurred on day 3 (15 March 2015) at 5 p.m. The minimum surface temperature drop was only 0.2°C. During this investigation, the highest ambient temperature
reading was 41.5°C. At this point, the bare wall surface showed a temperature reading of 35.5°C, whereas the wall behind the VGS achieved 29.1°C. The ambient temperature for both data sets peaked at 1 p.m. onwards and began to decline after 2 p.m. During this hour, the ambient temperature readings were ranged from 38°C to 40°C. From this experiment, it indicated that the most effective time for the VGS to achieve better thermal performance was at 3 p.m. The high ambient temperature led to higher surface temperature reduction. The lower interval of the VGS showed lower readings compared with the upper interval due to higher foliage coverage, which is estimated at 70 percent.

Conclusion

From this paper, it can be concluded that the application of vertical greenery system (VGS), where the shading element comprised of winged bean plants, managed to reduce the surface temperature through the benefits of shading. Overall, the average surface temperature drop recorded was 2.4°C (lower interval) and 1.1°C (upper interval). The maximum surface temperature drop achieved was at least 6.4°C and it occurred in day 2 of investigation at 3 p.m. (lower interval). The vertical greenery system (VGS) of using winged bean plant also proved to operate efficiently when it is exposed to high ambient temperature. The vertical greenery system of using winged bean plant will be tested on multi-storey residential balcony (transitional space) and the results can later be compared with the test cell data.

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