# QUASI-STATIC AND LOW-VELOCITY IMPACT RESPONSE ON FIBRE METAL LAMINATE

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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# ABSTRAK

Tujuan kerja penyelidikan ini adalah untuk mengkaji kesan tingkah laku gentian lamina logam di bawah keadaan muatan statik dan dinamik juga menentukan mekanisme kegagalan laminasi dengan menggunakan bahan-bahan yang berbeza seperti gentian karbon bertetulangkan polimer, gentian karbon prepreg satu arah, gentian kaca bertetulangkan polimer dan polimer polipropolina yang diperkuat sendiri. Gentian lamina logam terdiri daripada logam dan gentian komposit. Gentian lamina logam telah direka dengan menggunakan teknik pengacuan mampatan. Jenis logam lembaran yang telah dipilih ialah aloi aluminium 2024-0. Kepingan nipis logam digunakan sebagai lapisan atas dan bawah untuk gentian lamina logam. Epoksi termoset digunakan untuk melaminkan gentian kering seperti gentian karbon dan gentian kaca dengan kepingan logam tersebut. Kemudian, laminat akan dikeringkan dalam suhu bilik dan menggunakan beban sederhana untuk memberi tekanan. Walaupun yang terdiri daripada gentian prepreg telah ditekan dan dipanaskan dengan menggunakan mesin pemberi haba. Suhu dan tekanan yang digunakan adalah 125 ° C dan 4 bar. Manakala SRPP ditekan pada suhu 165 ° C dan 30 bar. Filem pelekat, polipropolina digunakan dan bertindak sebagai interlayer dalam gentian lamina logam. Filem polipropolina digunakan untuk melekatkan lapisan SRPP ke kepingan logam. Variasi  bahan yang digunakan, kelajuan, dan sesaran silang, adalah pembolehubah yang digunakan untuk menentukan tingkah laku mekanikal struktur dan diselidik. Keretakan matriks ditemui sebaik sahaja struktur impak oleh beban maksimum. Pemuatan berterusan yang menyebabkan kecacatan plastik dalam sistem aluminium. Kerosakan gentian dan penyingkiran setempat dalam sistem komposit serta interlayer pada antara muka (antara aluminium dan gentian) dan antara gentian diperhatikan. Kekuatan struktur bergantung kepada jenis bahan yang digunakan dan kelajuan. Kegagalan struktur yang disebabkan oleh permulaan penolakan dalam larutan komposit. Ujian lekapan kuasi-statik dan kesan hentakan rendah menggunakan dua buah mesin iaitu Instron 3369 dan 9350 yang dijalankan dengan kelajuan yang berbeza dan sesaran silang. Mekanisme kegagalan gentian lamina logam didapati serupa di bawah kedua-dua keadaan; quasi-statik dan hentakan rendah. Kerosakan itu dimulakan dengan lekukan dan impak daripada penghentak yang berdiameter 12.70 mm. Kemudian menghasilkan corak kegagalan yang sama pada selepas ujian. Model analisis telah digunakan untuk mensimulasikan tingkah laku mekanikal dengan menggunakan Abaqus versi 6.13. Keputusan analisis dibandingkan dengan keputusan experimen. Tingkah laku kegagalan gentian lamina logam telah diramalkan dan menunjukkan persetujuan yang baik dengan pemerhatian eksperimen. Hasil pengesahan analisis elemen terhingga dalam kedua-dua ujian menunjukkan persetujuan yang baik untuk pengukuran percubaan. Peratusan ketidaktepatan bagi kedua-dua ujian adalah kira-kira 1.43% dan 2%. Penggunaan lekukan kuasi-statik untuk meniru impak laju rendah dan membandingkan antara 4.5 m/s dan 100 mm/min untuk Al /CFR, Al/GFR, Al/SRPP dan Al/CFRP UD. Korelasi dinilai berdasarkan tenaga yang diserap untuk melebarkan gentian lamina logam. Daripada kedua-dua graf ini, tingkah laku antara kuasi-statik dan hentakan rendah adalah hampir sama dari segi perubahan daya yang digunakan untuk melepasi gentian lamina logam tersebut. Apabila kelajuan meningkat, daya impak dan lekukan maksimum juga meningkat.

# ABSTRACT

The aim of this research is to investigate the impact behaviour of fibre metal laminates under static and dynamic loading conditions and determine the failure mechanisms of the laminates with different materials such as plain weave carbon fibre reinforced polymer (CFRP), unidirectional prepreg carbon fibre reinforced polymer (CFRP), plain weave glass fibre reinforced polymer (GFRP) and self-reinforced polypropylene polymer (SRPP). The fibre metal laminates (FML) consist of metal and composite fibre. The fibre metal laminates were fabricated by using a compression moulding technique. A type of sheet metal chosen was aluminium alloy 2024-0. The sheet metal was used as top and bottom layer of the fibre metal laminate. A thermoset epoxy was used to laminate the dry fibres (plain weave CFRP and GFRP) with the sheet metal. Then, the laminates would be cured in a room temperature and used a moderate load for pressure application. Meanwhile, the fibre metal laminate, which consisted of prepreg fibre and SRPP was pressed and cured by using a hot press machine. The laminates were pressed then cured at 125°C with pressure of 4 bar. An adhesive film, polypropylene was used and acted as an interlayer in the fibre metal laminates. The polypropylene film was used to bond the SRPP layer to the sheet metal. Variation of materials used, speeds and crosshead speeds are manipulated variables were used to determine the mechanical behaviour of the structures and was investigated. Matrix cracking was found once the structure hit by a maximum load. A continued loading caused plastic deformation in the aluminium system. Fibre breakage and localised delamination in the composite systems as well as debonding at the interface (between aluminium and fibre) and between fibres were observed. The strength of the structure depended on the type of material used and speed. The failure of the structures was due to the initiation of delamination within the composite ply. Quasi-static indentation and low-velocity impact test used Instron 3369 and 9350, which was conducted by different speeds and crosshead speed. The failure mechanism of the fibre metal laminates were found to be similar which under both conditions. The damages were initiated by indentation and impact from a 12.70 mm indenter, which then produced a similar pattern after testing. Finite element models were developed to simulate the mechanical behaviour by using Abaqus finite element package. The finite element results were compared with the experimental results. The failure behaviour of the laminates were predicted and showed a good agreement with the experimental observation. The validation result of finite element analysis in both tests have shown good agreement to experimental measurement. The percentage error for both tests were about 1.43% and 2%. Quasi-static indentation was used to replicate low-velocity impact and was compared between 4.50 m/s and 100 mm/min for Al/CFRP, Al/GFRP, Al/SRPP and Al/CFRP UD. The correlation was evaluated based on energy absorbed to perforate the fibre metal laminate. From the findings, the pattern of during elastic and plastic deformation of quasi-static indentation result was almost identical to low-velocity impact result. When speed increased, maximum force of impact and indentation also increased.

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# LIST OF SYMBOLS

| | |
|---|---|
| $^{\circ}C$ | Degree Celsius |
| $\sigma$ | Stress |
| $T, T_a, T_f$ | The actual temperature |
| $n$ | Constant of plastic behaviour |
| $C$ | Sensitivity to strain rate |
| $\dot{\varepsilon}_0$ | Reference strain rate |
| $\varepsilon_p$ | Plastic strain |
| $\dot{\varepsilon}_p$ | Plastic strain rate |
| $E$ | Modulus elasticity |
| $\upsilon$ | Poisson's ratio |
| $\rho$ | Density |
| $A$ | Yield stress constant |
| $B$ | Strain hardening constant |
| $m$ | Thermal softening |
| $\varepsilon_0$ | Reference strain rate |
| $K$ | Melting and transition temperature |
| $D1, D2, D3, D4, D5$ | Fracture strain constant |
| $\bar{\varepsilon}^{pl}$ | Equivalent of the plastic |
| $\dot{\bar{\varepsilon}}^{pl}$ | Equivalent of a plastic strain rate |
| $\sigma^0$ | Static yield stress |
| $\bar{\sigma}$ | Yield stress at non zero-zero strain rate |
| $R(\dot{\bar{\varepsilon}}^{pl})$ | Ratio of yield stress at non zero-zero strain rate |
| $\omega$ | Damage parameter |
| $\Delta\varepsilon^{pl}$ | Increment of the plastic equation |
| $\sigma_m$ | Mean stress |
| $\hat{T}$ | Non-dimensionless temperature |
| $F_f^{\ t}$ | Breakage of fibre from the tension |
| $F_f^{\ c}$ | Buckle of fibre from the compression |
| $F_m^{\ t}$ | Crack of matrix from the tension |
| $F_m^{\ c}$ | Crush of matrix from the compression |
| $\sigma_{11}, \sigma_{22}, \sigma_{12}$ | Applied stresses |
| $\alpha$ | Coefficient of shear stress |
| $\delta^f{}_{eq}$ | Equivalent of a displacement in a FE when a stress reached to zero in stress-displacement |
| $\delta^0{}_{eq}$ | Equivalent of a displacement when the damage initiated |
| $\delta_{eq}$ | Equivalent of a displacement in FE |
| % | Percentage |
| d | Depth |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| 3D | Three dimensions |
| Al | Aluminium |
| ARALL | Aramid Reinforced Aluminium |
| ASTM | American Society for Testing and Materials |
| CARALL | Carbon Reinforced Aluminium Laminate |
| CFRP | Carbon Fibre Reinforced Polymer |
| CFRP UD | Carbon Fibre Reinforced Polymer Unidirectional |
| CNC | Computer Numerical Control |
| FE | Finite Element |
| Fmax | Maximum force |
| FML | Fibre Metal Laminate |
| FRP | Fibre Reinforced Plastic |
| GFRP | Glass Fibre Reinforced Polymer |
| GLARE | Glass Reinforced Aluminium |
| kN | kilo Newton |
| kPa | kilo Pascal |
| LVI | Low-Velocity Impact |
| M5 | Metric thread with screw diameter 5 mm |
| MPa | Mega Pascal |
| MQL | Minimum Quantity Lubricant |
| N | Newton |
| NFML | Novel Fibre Metal Laminate |
| QSI | Quasi-Static Indentation |
| SRPP | Self-Reinforced Polypropylene Polymer |

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