8.1 Summary

8.1.1 Summary of literature review

The previous work done can be summarized as follows;

- The main four manufacturing techniques for the FRP laminated built-up section structural members are; Hand lay up technique, Calendar technique, Pre-peg technique, and the Pultruded technique.
- A pultruded manufactured FRP laminated built up section was used to illustrate a real life material properties example of the used FRP column behavior, instead of just theoretical material properties.
- The used equations for analyze the material physical properties are illustrated from their first principles. Those equations are well established now, and they are commonly used to structurally analyze the laminated built up section analysis.
- The pultruded manufacturing technique is a continuous process for manufacturing prismatic sections of virtually any shape and long length and mass production (Creative Pultrusion 1988) offers the highest productivity to cost ratio.
- As the use of mathematical models are needed to study the behavior of the laminated built up sections, only few researches was done in the era of the 70's and 80's. Then on the 90's more intensive work had been done.
- Most of the work done for the statically analysis of the laminated built up sections, were done on plates. Real few researches were done on other structural members' forms.
- As for the studies of the interaction between the global and local buckling, in 1999 Ever J. Barbero illustrated theoretical/numerical prediction of the empirical interaction constant that used in design to account the interaction between the global and local buckling loads.
- Checking the behavior of the laminated built up section and validating the material section with the used equations for determining the overall section properties.
- Recently many researches had been done to reach a code of practice for the FRP laminated built up section, in order to identify all the usage aspects of those materials, and to achieve the maximum allowable stresses for the cross section.
- In 1997 U.S. Department of Defense "DOD" in collaboration with U.S. Federal Aviation Administration (FAA), developed a handbook of three volumes about the Polymer Matrix Composites.

The book is illustrated approved data of minutes of the handbook coordination group meetings, which are not mandatory but are acceptable for use in the development of structural design values to the FAA and to all branches of DOD.

- The primary purpose of the DOD handbook is the standardization of engineering data development methodologies related to characterization testing, data reduction, and data reporting of polymer matrix composite materials properties. It provides selected guidelines on other technical topics related to composites, including material selection, material specifications, material processing, design, analysis, quality control, and repair typical polymer matrix composite materials.
- "Zureick" et al. (1992) established an empirical equation for the critical overall buckling load determination for primarily uni-directionally FRP slender members subjected to axial loading in terms of Euler buckling equation as follows:

$$P_c = \frac{P_E}{1 + \left(n_s P_E / A_g G_{LT}\right)}$$

8.1.2 Summary of this study

8.1.1 Plates

- A plate member physical properties study from first principle is introduced, to verify the plates' cross section physical properties equations.
- Investigation for plates' different layers orientations combinations to predict the optimum layers orientation combination that gives the maximum overall physical properties (E_y) and (ν_{xy}).
- A verification study is done to choose the most representing computer simulation finite element model to be used.

8.1.2 Columns

- Different columns' cross sections are investigated to determine the columns' buckling loads capacities for each cross section.
- The cross section is composed of 10 different layers, with constant thickness; every layer represents 10% of the whole cross section thickness.
- Determination of the laminate layers arrangement to get the most effective overall section properties to resist the buckling failure is done by analyzing.

- The "H" shape column model is then investigated with many possible combination of the cross section laminas orientation to find out the maximum and the upper and lower limits of critical buckling loads.
- To study the effect of different initial imperfection values, two different initial imperfection values (1/1470 and 1/1000 of the column's height) are investigated.
- To study the effect of different initial imperfection direction, both initial imperfection directions (first toward the minor global axis and the other toward the major global axis) are investigated.
- To study the effect of different column's end conditions (Hinged-Hinged, Hinged-Fixed, Fixed-Fixed, and Fixed Free end conditions).
- Different columns shapes are investigated ("H" shape, "I" shape, square tube, rectangular tube, and tube with internal web cross sections) with combinations of (0/90)° (with respect to the global X axis) laminas orientation directions study investigated to identify the maximum column's buckling load capacity and its adjacent laminas orientation.
- Investigate the column's buckling load around the major axis of bending by restricting the side of the column around the minor axis with the ratio of r_x/r_y.
- An investigation is introduced to establish a factor to be added to Zureick buckling equation for FRP columns for the designer usage to be able to predict the buckling capacity of different (0/90)° layers' orientations arrangements for symmetrical section.

8.2 Conclusions

From the analytical work done, the following can be concluded for the cases studied:

8.2.1 Plates

- The FRP laminated plate that illustrated the most closer properties of the anitrophic FRP material to the isotropic material is layout prototype P4(0,90,0,90,0,90,0,90,0,90), noting that Young's modulus (E) of this prototype is about 66% of the maximum (E), and the Poisson's Ratio (ν_{xy}) is about 50% of the maximum reached value of Poisson's Ratio of a stacking sequence of the layers (90,90,90,90,90,90,90,90,90). i.e. all layers are arranged 90^0 to the global minor transverse axis.

8.2.2 Columns

- For the overall buckling of the "H" shape columns, the maximum overall load capacity is reached with the cross section that have the layers arranged with (10x90/0x0). The columns change their behavior from the local buckling mode to the overall buckling mode at the (L/r = 65).
- For layers arrangement (10x0), the columns change its behavior from the local buckling mode to the overall buckling mode at the (L/r = 30).
- For other layers arrangements, the local buckling found for $L/r < 30$, the overall buckling found for $L/r > 65$, and the interactive zone between overall and local buckling modes for $30 < L/r < 65$.
- Minor difference between major & minor buckling.
- The FRP columns length factors are similar to those of the isotropic columns for different end conditions (hinged-fixed (H-F), fixed-fixed (F-F), and fixed-free (F-Free), as follows:

  a- For (F-H) end conditions FRP columns;

  1) The local buckling zone ($L/r \leq 65$), both (F-H, and H-H) end conditions models have a non-significant difference (maximum 3.5% difference) of their local buckling capacities.
  2) The overall buckling zone (for both models) ($L/r > 130$), the overall failure capacity of the (H-H) end conditions columns is about 50% of the overall failure load capacity of the (F-H) end conditions columns, leading to column's height factor (F-H) = 0.7 of the column's height (H-H), complies with the isotropic materials.

  b- For (F-F) end conditions FRP columns;

  1) The local buckling zone ($L/r \leq 80$), both (F-F, and H-H) end conditions models have a non-significant difference (maximum 8.2% difference) of their local buckling capacities.
  2) The overall buckling zone (for both models) ($L/r \geq 200$), the overall failure capacity of the (H-H) end conditions columns is about 25% of the overall failure load capacity of the (F-F) end conditions columns, leading to column's height factor (F-F) = 0.5 of the column's height (H-H), complies with the isotropic materials.

  c- For (F-Free) end conditions FRP columns;

1) The local buckling zone (L/r ≤ 30), both (F-H, and H-H) end conditions models have the same values of their local buckling capacities.
2) The overall buckling zone (for both models) (L/r ≥ 100), the overall failure capacity of the (H-H) end conditions columns is about 400% of the overall failure load capacity of the (F-H) end conditions columns, leading to column's height factor (F-H) = double the column's height (H-H), complies with the isotropic materials.

- The magnitude and direction of the initial imperfection have no effect on the overall load capacity of the column.
- Studied columns with ("I" section, box section, rectangular section, box with stiffeners) proved that their buckling behavior is similar to those columns with "H" section.
- A modification of Zureick overall elastic buckling equation (modified Euler buckling equation) to include the effect of different layers orientation percentage to obtain the respective critical column's buckling load. The percentage of P(90°%)/P(100% 90°) is obtained, and studied to get the equation that gives the best representing for the data relationship. Then the output relationship is introduced to the PZureik equation and observed with the PAnsys obtained from the finite element program results.
- The equation that represents the polynomial trend to predict the overall buckling failure column capacity for different percentage of the (90 degrees) laminates orientation can be written as follows:

$$P_{Cr.of x\% la\min as} = P_{Zureik}\left(-0.005x^2 + 0.74x + 0.32\right)$$

Where:

$P_{cr\ of\ x\%\ laminas}$ = Empirical modified critical buckling failure load for x% of the laminas in the load direction.

$P_{zureick}$ = $P_c = \dfrac{P_E}{1+\left(n_s P_E / A_g G_{LT}\right)}$ = Zureick critical overall buckling failure load.

x = Percentage of the laminates that are oriented 90 degrees with respect to the X (global transverse - minor) axis (noting that this percentage is divided into two as the cross section is symmetric along its axis).

P_E= Euler overall buckling load capacity.

- For the overall buckling load capacity, the behavior of the other different cross sections ("I" shape, box, rectangular, and rectangular with stiffeners shapes) behaves exactly as the derived equations results for the "H" shape column.

- For the local buckling and the interactive zone between local and overall buckling, the derived equation doesn't represent the results of the buckling loads, as the buckling load depends on many other aspects including the load capacity of the cross section, the material shape, etc. These zones need more investigation.

8.3 Recommendations

From the presented study, it is evident that:

- Further researches are needed to cover the local buckling failure mode.
- Further researches are needed to cover the interaction between the local and the global buckling failure modes.
- Further researches are needed to cover the different loading conditions, for example torsional load, thermal load, biaxial load on the column's failure behavior.
- Further researches are needed to cover the shear modulus effect on the buckling load failure.
- Further researches are needed to cover the different joints type effect on the buckling behavior of the column.
- Further researches are needed to illustrate the behavior of the binding materials and their thickness effect on the behavior of material and structural elements.
- The delamination effects on the buckling failure load need to be studied.
- The effect of different layers thickness on the column buckling load capacity.
- The effect of material imperfection on the column buckling load capacity.
- The temperature changes effect on the buckling load capacity of the column.
- The creep effect on the buckling load capacity.