Experimental modeling of stability of single bay single storey frames
Ephraim M.E\textsuperscript{1} and Rowland-Lato E.O\textsuperscript{2}
1-Department of Civil Engineering, Rivers State University of Science and Technology, Port-Harcourt, Nigeria
2-Department of Civil Engineering, University of Port Harcourt, Nigeria
rowlandlato@yahoo.com
doi: 10.6088/ijcser.2014050030

ABSTRACT

Rigid frames subjected to critical loads are assumed to fail when the columns fail. The attached beams act as partial elastic restraints to the columns while the base supports are assumed to be pinned or fixed. This study presents the results of extensive laboratory investigation of the critical load of steel frames models of various stiffness values ($K = 0.5, 0.75, 1.0, 1.25$ and $1.5$) with fixed and pinned supports respectively. The critical load values and lateral deflection obtained from experiments are plotted against the beam column stiffness ratios $k_b/k_c$. Based on the test results, a linear relationship between the critical load and the selected stiffness ratios of the frame models was established within the elastic range. The results were used to validate the works of some recently proposed approximate formulae and empirical model for stability of frame. These results deviate from the selected approximate method approach by approximately $\pm$ 10%.

Keywords: Frames, Stability, Stiffness, Modelling, Critical Load.

1.0 Introduction

The critical load is apparently the most important parameter for judging the stability of frame structures. This has been the focus of many researchers who have developed various mathematical relationships for determining the critical load for rigid frame structures. The exact solution through full buckling analysis proposed at various stages by different researchers emanated from the development of stability functions to other concepts such as substitute frame, the modified Grinter frame, the equivalent column approach and the stiffness distribution technique among others (Allens, H.G, (1955)).

The stability of frames depend primarily on satisfying local stability of each member constituting the frame, then the secondary forces generated by geometric changes in the structure under loading are accounted for by second order P-delta analysis, especially for sway sensitive frames as classified by BS5950-2000. Graham proposed computerized method of analyzing for second order plane steel structures at any loaded stage up to and including collapse. Aristizabal-Ochoa also formulated simplified approach of solution of frame structure using second order analysis (Aristizabal- Ochoa J D, (2003)). This approach evaluates the effective length K-factor, the critical axial load and the sway magnification factor for the entire storey of plane frame structures The AISC-LRFD approach avoids the
imposition of any limits on the use of the second order analysis. It combines the column effective length factor and second order analysis to evaluate frame stability effects in beam to column member design.

This is done in recognition of the limitations of elastic; first order analysis to model the stability of frames with large axial column loads where the inelastic reduction of stiffness is significant. The contemporary design standards treat stability of frames structure through strength and stability criteria for beams and columns. The checks for in-plane and out-plane stability of beam to column are based on actual length of members.

The determination of the stability of frame structures as well as the effective length factor for whole or composite frames based on these methods is involving both analytical and computational complexity as well cost. Therefore need to develop simpler hand methods to support engineers in evaluating frames performance have formed the subject key in development of solutions to frame stability problems. Many researchers have developed various mathematical relationships for determining the influence of beam to column stiffness ratio \(k_b/k_c\) on the stability of rigid frames.

The concept of Equivalent Frame (Superimposition Technique) approach is based on the fact that characteristics of a single bay or single storey frame can be used to obtain similar characteristics of a multi storey or multi bay frame. Several researchers such as Bolton, Golderg[10] and McMin have employed this superimposition technique in investigating multi storey or multi bay frames. Stevens and Schidt[23] extend the Southwell plot to consider initial imperfection of the frame and provide a set of linear equations. Approximate methods have been developed in the works of various researchers: Anderson[3], Edmonds and Medland[7], Hoenderkamp[12], Orumu[21], Southwell[22], Steven[23].

While analytical approaches to stability of plane sway frames have received significant attention in the researches of Horne and Merchant, Hoenderkamp and Orumu. Technical literature also reveals a considerable number of experimental works with models of sway frames. A great number of these researches are associated with investigation of stability of sway frames in reinforced and pre-stressed concrete materials, as shown in the modelling approach by Fischer and Victor (2003) they however do not apply the principles of similitude relationship to their work, or application of similitude principles for extrapolation of laboratory data for application to life structures through the use of scale factors. In this work a detailed study of the relationship between the stiffness of the beam and level of restraint it gives to the column in the frame is investigated, its effect on single bay, single storey frames loaded directly on the column through experimental methods. The main specific objectives of this work is to provide Engineers the simplified empirical models for critical loads of frames, verified experimentally and comprehend the behavior, including the mechanism of resistance and failure of frame structures. Also to established relationship between beam to column stiffness ratio and stability parameters for the frame models under consideration, therefore validating selected approximate method of other researchers using the generated experimental data.
2.0 Theoretical background

The stability functions are used to account for various salient factors such as effect of material imperfection, inelastic behavior, shear deformation, Euler load and end conditions that contribute to the modification of member stiffness, other than the applied load. Table 1 presents the operations for rotations at the nodes for sway frame shown in Fig. 1.

<table>
<thead>
<tr>
<th>Action</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotate θB</td>
<td>CsK₁θB</td>
<td>4K₂θB</td>
<td>0</td>
<td>-s(1+c)K₁θB</td>
</tr>
<tr>
<td>Rotate θC</td>
<td>0</td>
<td>2K₂θC</td>
<td>SK₃θC</td>
<td>-s(1+c)K₃θC</td>
</tr>
<tr>
<td>Sway Δ</td>
<td>-s(1+c)K₁Δ/h</td>
<td>-s(1+c)K₃Δ/h</td>
<td>-s(1+c)K₃Δ/h</td>
<td>2s(1+c)(K₁+K₃)Δ/h</td>
</tr>
</tbody>
</table>

According to Horne and Merchant the critical conditions are as follows:

1. \( θ_B = θ_C \) and \( Δ = 0 \)  ------------------------------- Equation 1

2. \( θ_B = θ_C \) and \( Δ/h = m \ θ_B/2 \) ------------------------------- Equation 2

3. \( θ_B = θ_C = \frac{s(1+c)}{s+6K₂h/K₁} \)  ------------------------------- Equation 3

![Figure 1](image-url)
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The study is thus presented in two parts, namely: dimensional analysis and laboratory experimental tests. The details of these are covered in the relevant subsections, which follow.

2.1 Dimensional Analysis

The aim of this research is to produce direct models to represent prototype frames with dimensional properties in three categories. The models are to be tested to failure, and the results interpreted using the principles of similitude to verify the scaled up result with results obtained for the prototype by mathematical means.

The governing equation of the critical load for the one storey plane frame is assumed to be of the form

\[ F(P, E, L, H, A, I) = 0 \] (equation 4)

Where the assumed independent variables have the following definitions:

- **P**: Critical Load
- **L**: Span of Frame
- **H**: Height of Frame
- **E**: Modulus of Elasticity of frame material
- **A**: Cross sectional Area of column
- **I**: Moment of Inertia of column.

Assuming the modulus of elasticity E and the representative length L as dimensionally independent variables, equation 1 can be recast into an explicit form with dimensionless ratios:

\[ G\left(\frac{PL^2}{E}\frac{k_b}{k_c}\right) = 0 \] (equation 5)

\[ \frac{EL^2}{P} = \phi\left(\frac{k_b}{k_c}\right) \] (equation 6)

\[ P = \frac{1}{EI^2} \phi\left(\frac{k_b}{k_c}\right) \] (equation 7)

Since the constant P must be the same for model and prototype, the predictive condition is obtained by forcing the dimensionless ratios:

\[ \frac{P_p}{P_m} = \frac{E_m l^2}{E_p l^2} \phi_p\left(\frac{k_b}{k_c}\right) \phi_m\left(\frac{k_b}{k_c}\right) \] (equation 8)

Thus, the predictive scale factor for the critical load \( S_p = S_l^2 S_E S_P_m \)
Using the same material in model and prototype, i.e. $S_E=1$, the derived similitude conditions for loads, material properties and geometry are given in Table 2.

### 2.2 Experimental Materials and Procedure

The experimental aspects of the research were conducted in the Structures laboratory of the Rivers State University of Science and Technology, Port-Harcourt, Nigeria.

#### Table 2: Prototype and Model properties

<table>
<thead>
<tr>
<th>S.no</th>
<th>Property</th>
<th>Dimension</th>
<th>Scale factor</th>
<th>Prototype</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Loading</td>
<td></td>
<td>$S_E^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Critical load</td>
<td>$F$</td>
<td>1</td>
<td>$F_{pr(model)}$</td>
<td>$F_{pr(model)}$</td>
</tr>
<tr>
<td></td>
<td>Stress</td>
<td>$F/L^2$</td>
<td>1</td>
<td>$200kN/mm^2$</td>
<td>$200kN/mm^2$</td>
</tr>
<tr>
<td>2</td>
<td>Material Property</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Modulus of Elasticity</td>
<td>$F/L^2$</td>
<td>1</td>
<td>200kN/mm$^2$</td>
<td>200kN/mm$^2$</td>
</tr>
<tr>
<td></td>
<td>Poison Ratio</td>
<td>-</td>
<td>1</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>Geometry</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beam (mm)</td>
<td>$L$</td>
<td>2000</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Column (mm)</td>
<td>$L_1$</td>
<td>1000</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Column (mm)</td>
<td>$L_2$</td>
<td>1500</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Column (mm)</td>
<td>$L_3$</td>
<td>2000</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Column (mm)</td>
<td>$L_4$</td>
<td>2500</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Column (mm)</td>
<td>$L_5$</td>
<td>3000</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

#### 2.2.1 Materials

The materials employed in the fabrication of the test modes is high yield carbon steel reinforcement bars, and its properties are summarised in the Table 3 below.

#### Table 3: Laboratory Results of steel tensile test

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Diameter</th>
<th>Original Length L₀ mm</th>
<th>Final Length L mm</th>
<th>$\alpha$ mm</th>
<th>$\pi r^2$ mm$^2$</th>
<th>Stress $\sigma$ =P/A N/m m$^2$</th>
<th>Strain $\epsilon$ = $\alpha$/L x $10^3$</th>
<th>Young Modulus $E = \sigma /\epsilon$ (N/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10</td>
<td>40.00</td>
<td>40.48</td>
<td>0.048</td>
<td>19038</td>
<td>78.54</td>
<td>242.4 x 10$^{-3}$</td>
<td>202000</td>
</tr>
</tbody>
</table>
2.2.2 Model properties

The reinforcement bars were configured to portal frame specimen with fixed and pinned supports respectively as shown in Figure 2. The span of the beam was kept constant at 200mm and by varying height of the column several beam column ratio were achieved. The frames are classified according to their beam to column stiffness ratios in the value: 0.50, 0.75, 1.00, 1.25 and 1.50. The columns are fabricated as continuous members, with the beams framing into the columns connected via full fillet welds at the beam column interface.

2.2.3 Experimental Procedure

A total of 20 samples of portal frames were fabricated for both 10mm and 12mm (10 samples each). The objective of the test is to load the frame to failure in a bid to determine experimentally the critical load of the frame.

The experiment started with tensile testing of the steel reinforcement to determine its elastic modulus and ended with the compressive loading of the frame specimen of varying supports conditions (fixed and pinned supports) to determine the critical loads and deflection at which failure occurs.

Plate 1 shows the picture of the set-up. Specimens were placed on the loading frame platform. Spirit level and shim plates were used to ensure plumbness of the frames as they were being placed on the frame. The test frames were firmly secured to the loading frame base by bolting through the slots provided in the test frame supports.

The test frame was loaded with increments of 5kN until failure using ELE compressive machine with attached load gauge which has an accuracy of 0.1kN, while the deflection of the test models during loading were measured by the attached dial gauge which has an accuracy of 0.01mm.

Axial load application from the loading frame to the test frame is controlled in such a way that each of the frame columns receives approximately the same amount of load. This loading was achieved via the use of the fabricated load transfer frame illustrated in Fig 2b.
3.0 Discussion of results

The results obtained from the prototype frames and compared to the predicted results are presented in this section. Tables 4, 5, 6 and 7. below shows the summary of Laboratory $P_{CR}$ and Approximate $P_{CR}$ kN for both fixed and pinned support of different stiffness values ($K = 0.5, 0.75, 1.0, 1.25$ and $1.5$). Results obtained show that the effect of the stiffness values on the critical load is very significant. As the beam to column stiffness ratio increases there is a corresponding decrease in the critical loads for both the model and the predicted critical loads for either fixed or pinned support.

On the effect of support condition, this results show that the support condition of the frame structures has significant effect on the critical load. For a particular stiffness value the critical
load for specimen with fixed support is greater than that of pinned support. Also observed from the tables the resistance offered to critical load depends on the diameter of the frame structure. For any stiffness ratio and support conditions 12mm diameter bar offered greater resistance to critical load than 10mm diameter bar.

Considering Figure 3 to 7, the graphs show that within elastic limit both deflection and critical load $P_{cr}$ has significant relationship with the stiffness ratio $K_B/K_C$ respectively. While deflection increases with increased stiffness ratio $K_B/K_C$, the critical load $P_{cr}$ decreases with increased stiffness ratio $K_B/K_C$

For each stiffness ratio ($K_B/K_C$) value, support condition (fixed or pinned) and model frame specimen size (diameter), there is high level of correlation between the laboratory results and results from the approximate model solution confirm the adequacy of the model. This laboratory results therefore serves as a means of validating the proposed approximate model solution by Orumu. The subject of modelling is subject worthy of detailed attention in design codes, especially when design engineer have to tackle design of complex structures. While section 19.3.3 of ACI 318 permits the use of modelling in shelled structures, the extent of possible range of application of modelling techniques even to simpler problems is however underscored. Importance of modelling application to structural design and research can be of great economic benefit and advantage to developing countries where reduced scale models can be used at a reduced cost of fabrication, load requirement and instrumentation plus boosting participation in research and development.

### Table 4: $P_{CR}$ and $K_B/K_C$ Results for 10mm diameter specimen with fixed support

<table>
<thead>
<tr>
<th>Specimen identity</th>
<th>$K_B/K_C$</th>
<th>Deflection $\Delta \times 10^{-3}$ (mm)</th>
<th>Lab $P_{CR}$ (kN)</th>
<th>Approx predicted $P_{CR}$ (kN)</th>
<th>$P_{E}$ (kN)</th>
<th>Lab $P_{CR}/P_{E}$</th>
<th>Approx $P_{CR}/P_{E}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>0.50</td>
<td>14.48</td>
<td>90.0</td>
<td>114.30</td>
<td>96.90</td>
<td>0.929</td>
<td>1.180</td>
</tr>
<tr>
<td>1-2</td>
<td>0.75</td>
<td>11.91</td>
<td>60.0</td>
<td>59.20</td>
<td>43.06</td>
<td>1.393</td>
<td>1.375</td>
</tr>
<tr>
<td>1-3</td>
<td>1.00</td>
<td>5.53</td>
<td>34.2</td>
<td>36.82</td>
<td>24.22</td>
<td>1.412</td>
<td>1.520</td>
</tr>
<tr>
<td>1-4</td>
<td>1.25</td>
<td>3.22</td>
<td>30.0</td>
<td>25.05</td>
<td>15.50</td>
<td>1.935</td>
<td>1.616</td>
</tr>
<tr>
<td>1-5</td>
<td>1.50</td>
<td>1.87</td>
<td>24.0</td>
<td>18.09</td>
<td>10.77</td>
<td>2.229</td>
<td>1.680</td>
</tr>
</tbody>
</table>

### Table 5: $P_{CR}$ and $K_B/K_C$ Results for 12mm diameter specimen with fixed support

<table>
<thead>
<tr>
<th>Specimen identity</th>
<th>$K_B/K_C$</th>
<th>Deflection $\Delta \times 10^{-3}$ (mm)</th>
<th>Lab $P_{CR}$ (kN)</th>
<th>Approx predicted $P_{CR}$ (kN)</th>
<th>$P_{E}$ (kN)</th>
<th>Lab $P_{CR}/P_{E}$</th>
<th>Approx $P_{CR}/P_{E}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>0.50</td>
<td>27.34</td>
<td>100.0</td>
<td>237.08</td>
<td>200.92</td>
<td>0.498</td>
<td>1.180</td>
</tr>
<tr>
<td>2-2</td>
<td>0.75</td>
<td>17.10</td>
<td>96.0</td>
<td>122.72</td>
<td>89.30</td>
<td>1.075</td>
<td>1.374</td>
</tr>
<tr>
<td>2-3</td>
<td>1.00</td>
<td>10.75</td>
<td>75.0</td>
<td>76.35</td>
<td>50.23</td>
<td>1.493</td>
<td>1.520</td>
</tr>
<tr>
<td>2-4</td>
<td>1.25</td>
<td>8.49</td>
<td>50.0</td>
<td>51.95</td>
<td>32.15</td>
<td>1.555</td>
<td>1.616</td>
</tr>
<tr>
<td>2-5</td>
<td>1.50</td>
<td>6.37</td>
<td>38.0</td>
<td>37.51</td>
<td>22.33</td>
<td>1.702</td>
<td>1.680</td>
</tr>
</tbody>
</table>
Table 6: $P_{CR}$ and $K_B/K_C$ Results for 10mm diameter specimen with pinned support

<table>
<thead>
<tr>
<th>Specimen identity</th>
<th>$K_B/K_C$</th>
<th>Deflection $\Delta x 10^{-3}$ (mm)</th>
<th>Lab $P_{CR}$ (kN)</th>
<th>Approx predicted $P_{CR}$ (kN)</th>
<th>$P_E$ (kN)</th>
<th>Lab $P_{CR}/P_E$</th>
<th>Approx $P_{CR}/P_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>0.50</td>
<td>14.48</td>
<td>24.0</td>
<td>23.77</td>
<td>96.90</td>
<td>0.248</td>
<td>0.245</td>
</tr>
<tr>
<td>3-2</td>
<td>0.75</td>
<td>10.13</td>
<td>15.0</td>
<td>13.59</td>
<td>43.06</td>
<td>0.348</td>
<td>0.316</td>
</tr>
<tr>
<td>3-3</td>
<td>1.00</td>
<td>6.45</td>
<td>10.0</td>
<td>8.92</td>
<td>24.22</td>
<td>0.413</td>
<td>0.368</td>
</tr>
<tr>
<td>3-4</td>
<td>1.25</td>
<td>4.81</td>
<td>7.4</td>
<td>6.11</td>
<td>15.50</td>
<td>0.477</td>
<td>0.394</td>
</tr>
<tr>
<td>3-5</td>
<td>1.50</td>
<td>1.52</td>
<td>6.0</td>
<td>4.44</td>
<td>10.77</td>
<td>0.557</td>
<td>0.412</td>
</tr>
</tbody>
</table>

Table 7: $P_{CR}$ and $K_B/K_C$ Results for 12mm diameter specimen with pinned support

<table>
<thead>
<tr>
<th>Specimen identity</th>
<th>$K_B/K_C$</th>
<th>Deflection $\Delta x 10^{-3}$ (mm)</th>
<th>Lab $P_{CR}$ (kN)</th>
<th>Approx predicted $P_{CR}$ (kN)</th>
<th>$P_E$ (kN)</th>
<th>Lab $P_{CR}/P_E$</th>
<th>Approx $P_{CR}/P_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-1</td>
<td>0.50</td>
<td>24.23</td>
<td>47.4</td>
<td>49.20</td>
<td>200.92</td>
<td>0.236</td>
<td>0.245</td>
</tr>
<tr>
<td>4-2</td>
<td>0.75</td>
<td>16.70</td>
<td>29.4</td>
<td>28.18</td>
<td>89.30</td>
<td>0.329</td>
<td>0.316</td>
</tr>
<tr>
<td>4-3</td>
<td>1.00</td>
<td>13.11</td>
<td>20.0</td>
<td>18.49</td>
<td>50.23</td>
<td>0.398</td>
<td>0.368</td>
</tr>
<tr>
<td>4-4</td>
<td>1.25</td>
<td>12.50</td>
<td>12.0</td>
<td>12.68</td>
<td>32.15</td>
<td>0.373</td>
<td>0.394</td>
</tr>
<tr>
<td>4-5</td>
<td>1.50</td>
<td>7.11</td>
<td>12.0</td>
<td>9.20</td>
<td>22.33</td>
<td>0.538</td>
<td>0.412</td>
</tr>
</tbody>
</table>

Figure 3: Plot of critical load versus stiffness ratio for fixed support condition for 10mm and 12mm size model frames.
Figure 4: Plot of critical load versus stiffness ratio for pinned support condition for 10mm and 12mm size model frames.

Figure 5: Plot of deflection versus stiffness ratio for both fixed and pinned support condition.
Figure 6: Plot of critical load versus deflection for 10mm and 12mm size model frames

Plate 2: Sway failure Mode
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Figure 7: Plot of critical load versus Stiffness ratio for 10mm and 12mm size model frames

Plate 3: Non Sway failure Mode

Plate 4: Out of Plane failure Mode
4. Conclusion

The study reported here in was aimed at determining the effect of critical load on the stability of single bay single storey frames. The study was prompted by the observation of building failures in recent past in which the frame works are seriously affected because of inadequate analysis and determination of the critical load of structural elements.

Based on the analysis and discussion of these results, the following specific conclusions were arrived at:

1. The critical load \( P_{cr} \) and lateral deflection of the frame generally have significant relationship within the elastic limit and depend on the beam-column stiffness ratio \( K_B/K_C \).

2. The critical load \( P_{cr} \) depends on the support condition of frame structure. The frames with fixed support offer great resistance to critical load \( P_{cr} \) compare to that of pinned support, the more rigid the support condition, the greater the value of the critical load.

3. The beam-column stiffness ratio \( K_B/K_C \) has significant effect on the value of the critical load \( P_{cr} \). Frames structure with lower stiffness ratio \( K_B/K_C \) required greater critical load to cause lateral deflection and as the stiffness ratio \( K_B/K_C \) is increased the critical load decreases with corresponding increase in lateral deflection. Hence maximum stability is achieved by lower stiffness ratio \( K_B/K_C \) frames.

4. The size of the frame has significant effect on the value of the critical load. For same stiffness ratio \( K_B/K_C \) value, the critical load for diameter 12mm model frame specimens are twice that of diameter 10mm model frame specimen. It implies that, the resistance offered by the frame structures to applied load depends on the size. That is the bigger size of the frame the greater the load it can withstand before failure occurs.

5. Here the result shows that the Laboratory \( P_{CR} \) and Approximate model solution by Orumu [21] \( P_{CR} \) kN for both fixed and pinned support of different stiffness values \( K = 0.5, 0.75, 1.0, 1.25 \) and 1.5) are within 10% accuracy.

5. Recommendation

1. It is recommended that further research work should be carried out using multi storey frame and 3-dimensional frame model.

2. Also a wider range of beam-column stiffness ratio \( K_B/K_C \) should be considered.

3. Since support condition plays a vital role in providing additional frame resistance, a means of calibrating the support condition should be adopted in a way that factors can be easily employed to equations to simulate actual support capacities in an equation and if not found wanting, should be embraced by practicing Engineers.
6. References


Experimental modeling of stability of single bay single storey frames
Ephraim M.E and Rowland-Lato E.O


