Elastoplastic Behavior of Wide Flange Beam - to-Wide Flange Column Welded Connections

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Abstract. A beam-to-column connection is considered to be one of the most critical sections of various types of load-carrying structures. Many parameters such as the geometrical and material properties of both beams and columns influenced its performance. The purpose of this study is to derive analytical models for the connection’s yield and ultimate strength and displacements using the depth of wide flange (WF) beam and WF-column, and the length of WF-beam as design parameters. Experimental tests involved testing of three specimens until reaching their maximum strength. The behavior of the connection observed in the experiment were employed in the finite element analyses (FEA), where the thirty numerical models generated with the parametric script in SolidWorks, provided the design information for the mechanical properties. Lastly, the derivation of analytical formulae used to predict the mechanical properties of wide flange beam-to-wide flange column connections employed regression analysis. In conclusion, (1) There is a good agreement between FEA and test results, (2) The dimensional parameters $L_b/D_b$ and $D_c/L_b$ ratios have been found to significantly characterize the elastic-plastic properties of fully welded beam-to-column connections with stiffeners, and (3) The mechanical properties of the connections can be well predicted by the derived analytical formulae.

1. Introduction

The beam-to-column connections assume a vital part in the overall performance of a structure. Consequently, inadequate connections can fail the structure regardless of how adequately designed the structural members are. Parameters such as geometrical and mechanical properties of the material used and detailed arrangement of the column influence the performance of the connection. Thus, changing the geometrical properties of connected elements can modify the status of their stresses, strains, and the structure failure mode [1]. Recent investigations on the elastic-plastic behavior of beam-to-column connection focused on the parametric investigation of a hollow structural column to WF-beam connections and their impact within the structural engineering profession [2-5]. In addition, existing studies that derive formulae that can estimate beam-to-column connections’ strength and displacements are relevant only to a wide flange beam-to-hollow structural steel (HSS) column connections. The present study derived parametric formulae that can predict WF beam-to-WF column
connection’s behavior in terms of local strengths and displacements (i.e., yield load, ultimate load, yield deformation, ultimate deformation). WF beam-to-WF column welded connection is a popular type of connection in the Philippines.

Kamba et al. and Hassan et al. [3-4] obtained analytic formulae through regression analysis that effectively predicted the behavior of connections in a numerical study on circular hollow sections (CHS) connections. Simulation of numerical models under three loading conditions, a compression load, tension load and moment, used the parameters diameter to thickness ratio \( (D/t) \) and the flange width to diameter ratio \( (B_f/D) \) [3], length of gusset plate, and connection configuration [4]. In a nutshell, the behavior of CHS connections is dependent upon these parameters.

The aforementioned discussion highlights the need to develop analytical models that can predict well the elastic-plastic behavior of beam-to-column connections, particularly beams and columns made of wide flange sections. Lack of understanding, poor design of connection and ignoring the actual response of connection in the structural analysis may lead to inadequate structural design and consequently lead to disaster [6]. In response to this problem, the study proposes to determine the elastic-plastic behavior of W-beam-to-W-column moment connections by obtaining analytical formulae. The findings apply to conventional frame analysis to predict the realistic connection performance of steel frames. Thus, a new theory on building design may be arrived at.

### 2. Materials and Methods

#### 2.1. Experimental Program

**2.1.1. Materials.** To conduct a full-scale experimental test, a test rig was considered to accommodate a smaller specimen, 2.5-meter-height columns (WF 8x24) and 1.6-meter-span cantilever beams (WF 4x13, WF 6x15 and WF 8x24).

Experimental materials used were A36 wide flange sections and A36 steel plates. The beam-to-column connections were designed in accordance with the American Institute of Steel Construction [6-8], and National Structural Code of the Philippines [9], while the horizontal stiffeners followed the American Welding Society [10-11] specification. In the WF specimens, the beam flanges were connected to the column flange, and the sides of the beam web to the column flange by fillet welds. Details of the connections and their configurations are shown in Table 1 and Figure 1, respectively.

**Table 1.** Details of Specimens for Experimental Tests.

| Specimen | Column | Beam | Length of the beam (mm) | Fillet weld Size (mm) for A36 steel | Length in each side of the web (in.) | Length of flange weld (in.) |
|----------|--------|------|-------------------------|-----------------------------------|-----------------------------------|---------------------------|
| m14-0.15 | WF4x13 | 1600 | 6                       | 6.33                             | 4.06                              |
| m9-0.15  | WF 8x24| 1600 | 6                       | 4.97                             | 5.99                              |
| m7-0.15  | WF 8x24| 1600 | 6                       | 8.85                             | 6.495                             |

**Figure 1.** Configuration of the Specimens.
To avoid confusion, the names of the specimens were matched to their numerical designation.

2.1.2. Test Procedure. Data acquisition of the load applied on the beam through the load cell involved the use of LabView software and National Instruments (NI) data acquisition devices. As shown in Figure 2, a compression load cell was connected to the NI 9219 universal analog input module, then plugged into the NI CompactDAQ system and connected back into a laptop. A steel ruler was positioned at the loading frame to measure the vertical deflection of the specimens at increasing load.

![Test Setup](image)

Figure 2. Test Setup.

A recording of the initial zero-load reading began the test. Loads were applied to the cantilever beam at 1.4 m from the face of the column using a hydraulic jack. The loading of the specimen was increased until it reached the ultimate strength.

2.2 Numerical Modeling

2.2.1. Finite Element Model. Finite element models of beam-to-column connections under monotonic loads were analyzed using SolidWorks 2016 software.

A set of numerical models were developed according to the tests’ set-up, respecting the same geometry, boundary conditions and the applied loading in the experimental tests.

A displacement control nonlinear static analysis was performed, employing a Von-Mises plastic model type to accurately simulate the plastic behavior of the connections. In FE simulations, the values of material properties of A36 steel in a nonlinear simulation were the default values provided SolidWorks software except for the Tangent Modulus that was inputted through the Material dialog box.

3. Results and Discussion

3.1. Experimental Test Results

Force and beam’s deformation at yielding and ultimate points were determined through experimental investigations. Table 2 shows the elastic-plastic properties of the three specimens considered. Bending stresses $\sigma$ were taken from theoretical computations, employing the formula:

$$\sigma = \frac{PL_h}{S_x}$$

[1]
where \( \sigma \) = bending strength of the beam, \( S_x \) = Section modulus of the beam along the axis of the beam, and 
\( L_b \) = distance from the face of the column to the point along the beam where the load is applied.

### Table 2. Summary of Test Results (Actual).

| Specimen | \( P_L \) (MPa) | \( P_Y \) (kN) | \( P_u \) (kN) | \( \delta_{PL} \) (mm) | \( \delta_{y} \) (mm) | \( \delta_{u} \) (mm) | \( \sigma_{Y} \) (MPa) | \( \sigma_{u} \) (MPa) |
|----------|----------------|--------------|---------------|-----------------|-----------------|-----------------|----------------|----------------|
| m14-0.15 | 18.65          | 19.35        | 25.61         | 39.69           | 44.45           | 252.12          | 304.26         | 402.77         |
| m9-0.15  | 27.54          | 29.76        | 49.32         | 38.10           | 41.28           | 139.70          | 344.60         | 570.99         |
| m7-0.15  | 29.96          | 39.76        | 74.45         | 52.39           | 257.81          | 162.55          | 304.58         | 304.58         |

The design weld size for all connections was the maximum weld theoretically computed. This is the prime reason the connections did not show visible cracks. At the early stage of loading, m14-0.15 already manifested small lateral buckling to its right. There was also a noticeable deformation in the panel zones, especially in m7-0.15 and m9-0.15 since larger loads were applied to the two connections to deform them. Added column stiffeners added strength to the columns as well.

### 3.1.1. Summary of the Experimental Tests.

The main findings of the experimental investigations were the \( P_u/P_y \) (= 1.32, 1.66 and 1.87) and the Proportional Limit (= 0.63\( P_y \), 0.49\( P_y \), and 0.75\( P_y \)) ratios of the specimens m14-0.15, m9-0.15, and m7-0.15, respectively. These ratios will form the points A, B, and C of the trilinear curves of the numerical models, following the proposed trilinear model of Kamba and Taclendo [3] and Hassan et al. [4]. Taking the average \( P_u/P_y \) of the three specimens gave 1.62. \( P_u \), the load required to reach the maximum load a beam can carry. The Proportional limit is the point where the connection behaves elastically. This is the 1st point of the load-deformation curve and is located at an average of 0.62\( P_y \).

### 3.1.2. Comparison between Experimental and FEA Results.

Figures 3 (a) to (c) show the von Mises stress distribution on the assemblies of m14-0.15, m9-0.15 and m7-0.15 simulated in SolidWorks. The variation of colors represents the intensity of the stress developed at all sections of the assembly and the magnitude of which is shown in the color bar at the right.

![Figure 3. FEA Von-Mises stress distribution for (a) m14-0.15, (b) m9-0.15 and (c) m7-0.15.](image)

Graphs in Figure 4 summarize the comparison of load-deformation (\( P-\Delta \)) of the experimental to the FEA results. \( P_L \), \( P_Y \) and \( P_u \) are represented in the curves as circles and triangles. The circles indicate the results in the experimental tests while the triangles indicate the FEA results. It can be observed that ultimate loads from experimental investigation and finite element simulations have closer values than that of yield loads. Further, it can be seen in the curves that FEA well-estimated m14-0.15,
underestimated m9-0.15, and overestimated m7-0.15 a little to the test results. However, good correspondences have been found between the experimental stresses and FEA stresses, hence, it can be safely said that there is a good agreement between the experimental and numerical results, particularly in the plastic domain.

![Comparison of Experimental and FEA results](image)

**Figure 4.** Comparison of Experimental and FEA results (a) m14-0.15, (b) m9-0.15 and (c) m7-0.15.

### 3.2 Finite Element Analysis Results

Tables 3 shows the mechanical properties of beam-to-column connections obtained from finite element simulations of 27 models. In the analyses, length of the beam to its depth and the depth of the column to the beam’s length \((L_b/D_b, D_c/L_b)\) were chosen as design parameters where \(L_b\) the length of the beam is, \(D_b\) is the depth of the Wide Flange beam, and \(D_c\) is the depth of the Wide Flange column. The designation of specimens was taken from the loading configuration - monotonic loading. Specimens under monotonic loadings were represented by the prefix, “m”. The first numerical designation, i.e., 14, 9, 7, 5.5, 4.6, and 4, represented the ratio of the beam’s length over its depth. The ratio of the column’s depth over the beam’s length of the specimen was indicated by numbers 0.15, 0.18, 0.22, 0.25 and 0.29. The results of the experimental test conducted on three specimens are also shown in the table marked * at the specimen’s column.

**Table 3. FEM Results of specimens.**

| SPECIMEN | COLUMN | BEAM | PL (kN) | \(\delta_{PL}\) (mm) | Py (kN) | \(\delta_y\) (mm) | Pu (kN) | \(\delta_u\) (mm) |
|----------|--------|------|--------|---------------------|--------|-----------------|--------|-----------------|
| m14-0.15* | WF 8x24 | WF 4x13 | 18.65  | 39.69  | 19.35  | 44.45  | 25.61  | 252.12 |
| m9-0.15*  | WF 6x15 | WF 4x13 | 27.54  | 38.10  | 29.76  | 41.28  | 48.22  | 139.7 |
| m7-0.15*  | WF 8x24 | WF 4x13 | 34.38  | 9.97   | 55.45  | 29.33  | 74.45  | 258.81 |
| m5.5-0.15 | WF 10x22 | WF 6x15 | 43.92  | 8.09   | 70.84  | 12.4   | 114.76 | 24.8 |
| m4.6-0.15 | WF 12x26 | WF 6x15 | 48.16  | 8.36   | 77.68  | 13.93  | 125.84 | 23.35 |
| m4-0.15   | WF 14x22 | WF 6x15 | 51.03  | 11.33  | 82.31  | 28.33  | 133.34 | 118.98 |
| m14-0.18 | WF 10x26 | WF 4x13 | 52.77  | 9.03   | 37.06  | 37.77  | 60.04  | 212.23 |
| m9-0.18   | WF 6x15 | WF 4x13 | 62.77  | 9.03   | 101.24 | 40.72  | 100.15 | 133.5 |
| m7-0.18   | WF 8x24 | WF 4x13 | 72.27  | 9.03   | 101.24 | 40.72  | 100.15 | 133.5 |
| m5.5-0.18 | WF 10x22 | WF 4x13 | 82.77  | 9.03   | 101.24 | 40.72  | 100.15 | 133.5 |
| m4.6-0.18 | WF 12x26 | WF 4x13 | 93.27  | 9.03   | 101.24 | 40.72  | 100.15 | 133.5 |
| m4-0.18   | WF 14x22 | WF 4x13 | 103.77 | 9.03   | 101.24 | 40.72  | 100.15 | 133.5 |
| m14-0.22 | WF 14x30 | WF 4x13 | 114.27 | 9.03   | 101.24 | 40.72  | 100.15 | 133.5 |
3.3 Analytical Analysis of the Numerical data

3.3.1. Relationship between Applied Load \( P \) and \( L_b/D_b \) and \( D_c/L_b \) The larger the \( D_c/L_b \) ratio and smaller the \( L_b/D_b \) ratio, the higher the strength the specimens have. This is evident in the graphs of \( P_y \) and \( D_c/L_b \) and \( P_u \) and \( D_c/L_b \) in Figure 5 (a) and (b). Power trendlines in Microsoft Excel were also added to give a clear illustration of the effect on the mechanical properties of the connections by the predictors. The high values of the Pearson correlation coefficient \( r \) significantly indicate a strong correlation of variables. In summary, the proportional limit, yield and ultimate strengths of the specimens displayed similar behavioral pattern and close values of \( r \).

![Graphs showing relationship between Load Applied and \( D_c/L_b \) for \( P_y \) and \( P_u \).](image)

(a) \( P_y \) vs. \( D_c/L_b \) (b) \( P_u \) vs. \( D_c/L_b \).

3.3.2. Relationship between Deformation \( \delta \) and \( L_b/D_b \), \( D_c/L_b \) Generally, the larger the \( L_b/D_b \) and \( D_c/L_b \) ratios, the larger the deformation as shown in both figures in Figure 6 a, b. The graphs below exhibit the direct relationship between deformation and the predictors. In the \( D_c/L_b \) ratios, 0.18 showed the least deformation in the graph despite 0.15 being the lowest \( D_c/L_b \) ratio. However, in a general sense, the deformation of the specimens increases as the \( D_c/L_b \) ratio increases.
Figure 6. Relationship between Deformation and $L_b/D_b$ (a) $\delta_y$ vs. $L_b/D_b$ and (b) $\delta_u$ vs. $L_b/D_b$.

3.3.3. Modeling the mechanical properties of beam-to-column connections. Dimensional analysis, per se, analyzes the relationships between physical quantities. A physical quantity is represented non-dimensionally by a non-dimensional product of all physical quantities related to it. For example, the physical quantities related to the yielding load $P_y$ of the connections are the length to the depth of the beam ratio and the depth of the column to the length of the beam ratio as per the high value of correlation coefficients. In the analytical modeling, these physical quantities were taken into account to obtain values closer to the test and FEA results.

Considering the in-depth analysis on the relationship between the mechanical properties of beam-to-column connections to the geometrical and material parameters performed in the previous sections, the yield load parameter is

$$P_y = X_1(L_b/D_b)^aX_2(D_c/L_b)^bX_3\varepsilon$$

where, $\varepsilon$ is the error. Dependent variables are the mechanical properties of the connection while the independent variables are the geometric parameters $L_b/D_b$ and $D_c/L_b$. A power formula was used because it is the best-fit curve for the FEA and test data. The numerical values for $X_1$, $X_2$, $X_3$, $a$, and $b$ were determined using the method of least squares with 3 test and 27 FEA results. Performing the said statistical technique for all mechanical properties, the analytical models are the following:

$$P_y = \sigma_yL_b^2[0.0047(L_b/D_b)^{-1.458}(D_c/L_b)^{0.582}] \quad (N)$$

$$P_u = \sigma_yL_b^2[0.0067(L_b/D_b)^{-1.42}(D_c/L_b)^{0.59}] \quad (N)$$

$$\delta_y = L_b[6.5754E^{-6}(L_b/D_b)^{0.7412}(D_c/L_b)^{0.1726}] \quad (mm)$$

$$\delta_u = L_b[9.1012E^{-6}(L_b/D_b)^{1.2962}(D_c/L_b)^{0.2189}] \quad (mm)$$

where, $\sigma_y$ is the yield strength of the beam and column section expressed in terms of $N/mm^2$ and $L_b$ is the length of the WF beam in millimeter, $D_b$ is the depth of the WF beam in millimeter and $D_c$ is the depth of the WF column in millimeter.

3.3.4. Comparison between Experiment, FEA and Predicted results. The comparison of the load-deformation curves of the test (m14-0.15, m9-0.15 and m7-0.15) and FEA to the predicted values are shown in Figures 7 (a), (b) and (c). The trilinear curve models were plotted using the analytical models derived in the previous section. The predicted values tend to overestimate the experimental and FEA results at a smaller $L_b/D_b$ ratio. It is evident in the graphs that the analytical models yielded good prediction for m14-0.15 ($L_b/D_b = 14$), but these overestimated prediction for specimens m9-0.15 ($L_b/D_b = 9$) and m7-0.15 ($L_b/D_b = 7$).
4. Conclusions
1) There is a good agreement between FEA and test results, particularly in the plastic domain.
2) The dimensional parameters $L_b/D_b$ and $D_c/L_b$ ratios have significantly characterized the elastic-plastic properties of fully welded beam-to-column connections with stiffeners.
3) The mechanical properties of the connections can be well predicted by the derived analytical formulae obtained by the nonlinear regression analysis.
4) There is a good correlation between the FEA results and the derived analytical formulae.

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