CHAPTER I
INTRODUCTION

1.1 OVERVIEW OF DESIGN PROBLEM

1.1.1 Background

In a rigid steel moment connection most of the moment is transferred through the beam flanges to the column in the form of a couple. The couple is formed from this moment and acts at a moment arm equal to the depth of the beam (center-to-center of the flanges if directly welded). The beam is therefore exerting a tensile force through one flange and a compressive force through the other as shown in Figure 1.1.

The forces resulting from the transfer of moment from the beam to the column are relatively large concentrated forces. At the beam tension flange of the connection, the pull created on the column flange may be great enough to cause slight deformation of the flange. The strength of the column will therefore be impaired. Similarly, the compressive force entering through the other flange may be large enough to cause instability in the column web (Salmon and Johnson 1995). The connection can be improved by providing additional strength to the column connection where the load is being transferred in the form of stiffeners, Figure 1.1. Stiffeners are placed on the column at the locations of the beam flange forces to prevent distortion of the column flange where the beam exerts the tensile loading and web yielding and crippling at the compression loading. Stiffeners are therefore designed to prevent local column failure created by large beam forces at the moment connection (Segui 1994).

1.1.2 Current Design Model

Column stiffeners can be designed to prevent local flange bending, local web yielding, local web crippling, and compression buckling of the column. The *AISC Load and Resistance Factor Design Specification for Structural Steel Buildings* (1993) contains design strengths for these limit states at the column in Chapter K. If the applied factored force transmitted by the beam flange exceeds the column design strength, $\phi R_n$, for any limit state condition, stiffeners must be used for the full strength of the moment.
Figure 1.1 Moment Transfer Couple
connection to be developed.

The AISC LRFD Specification (Load 1993) gives rules for sizing stiffeners based on the applied loading and the controlling column side-limit state but does not provide rules for assigning force values to the stiffeners. In Volume II of the AISC LRFD Manual of Steel Construction (Manual 1993) a method is suggested for assigning stiffener forces. It is noted that in this model, the column is assumed to support the total applied moment until the limit state with the lowest design strength is exceeded. It is at this moment that the force begins to be distributed to the stiffeners. This method therefore assumes that the stiffeners do not receive any load applied at the connection until the lowest column limit state design strength is exceeded. Figure 1.2 shows the force resisted by the stiffeners compared to the total applied load if the AISC procedure is used.

![Stiffener Load Distribution](image)

**Figure 1.2** Stiffener Force Based on AISC Manual Procedure
This model can not be correct because it does not follow the behavior of the connection. Moment connections are designed to transfer moments applied to the column in the form of tensile and compressive forces. Stiffeners are therefore added to the column at the application of the loads to provide support and stability. Welds are used to provide a physical connection between the stiffeners and the column flanges and web. These welds therefore provide a continuous load path between the column and stiffeners allowing the stiffener to resist force as soon as loading is applied.

1.1.3 Objective of Study

To prove that the current model assumptions for assigning stiffener loads are inadequate, testing was performed on two W-shaped column sections subjected to tensile loading acting through a plate representing the beam flange. Stiffeners were added to the column at the point of application of the load (at the plate location). Strain gages were attached to the column stiffeners and web. During loading, strain readings were obtained to monitor the distribution of load between the column and the stiffeners. Finite element modeling was also performed to ensure the validity of the test and test procedure. Finite element modeling was also done on a larger column section to support the accuracy of the model for W-shaped sections of different geometry.

1.2 AISC COLUMN SIDE LIMIT STATE DESIGN STRENGTH

The current design procedures used for column stiffener design are found in the LRFD Specification for Structural Steel Buildings, Chapter K (Specifications 1993). Chapter K of the Specifications includes the column strength requirements that must be considered in beam-to-column connection design. Each of the applicable column limit states are analyzed to determine if additional reinforcement is needed to support the load on the connection.

The LRFD Specifications consider the flange and web strengths of the column separately. The flange limit state is local flange bending while the web section includes the following limit states because most of the compressive force is transmitted through the web:

- Local web yielding (tensile or compressive)
• Web crippling
• Compression buckling of the web
• Panel zone web shear

The size of stiffener required depends on which limit state is exceeded.

Local flange bending can occur when concentrated tensile forces are applied to the column. The design strength of the flange from Section K1.2 of the *Specifications* is $\phi R_n$, where:

$$\phi = 0.90$$

$$R_n = 6.25t_f^2 F_{fyf}$$

and $t_f$ = flange thickness, $F_{fyf}$ = yield stress of the flange material.

Stiffeners that extend to at least half the depth of the column web are required when this limit state is exceeded and should be located at the application of the tensile force, Figure 1.3. These stiffeners must be welded to the loaded flange and the weld between the stiffener(s) and the web must be large enough to allow the unbalanced force in the stiffener to be transmitted to the web (*Specifications* 1993).

When a force is being transmitted through the web, local web yielding may occur. The strength of the member depends upon the location of the concentrated force(s) relative to the top of the column when considering this limit state, Figure 1.4. The design strength of the web from Section K1.3 of the *Specifications* is as follows:

• When the concentrated force is located at a distance greater than the depth of the member away from the member end,

$$\phi = 1.0$$

$$R_n = (5k + N) F_{yw} t_w$$

where $k$ = distance from outer face of flange to web toe of fillet, $N$ = length of bearing, $F_{yw}$ = yield stress of web material, $t_w$ = web thickness.

• When the concentrated force is acting at a distance less than or equal to the depth of the member d from the member end,
Figure 1.3 Local Flange Bending Stiffener Requirements
Figure 1.4 Local Web Yielding Stiffener Requirements
φ = 1.0

\[ R_n = (2.5k + N) F_{yw} t_w \]

When tensile forces acting normal to the flange exceed this requirement, stiffeners must be used and welded to the loaded flange. Similarly, for an excessive compressive force acting normal to the flange, stiffeners are added and may either bear on or are welded to the loaded flange. These stiffeners again must be at least one-half the depth of the web. The stiffeners, in both cases, must be connected to allow the force to be transmitted to the stiffener. The weld connecting the stiffener to the web is therefore designed to be large enough to transmit this unbalanced force in the stiffener to the web (Specifications 1994).

Web crippling only applies to compressive concentrated forces. The strength of the member required to prevent web crippling again depends on the location of the applied force relative to the column end. From Section K1.4 of the Specifications:

- If the compressive force is applied at a distance greater than or equal to one half the depth of the member from the member end,

  \[ \phi = 0.75 \]

  \[ R_n = 135t_w^2 \left\{ 1 + 3(N/d)(t_w/t_f)^{1.5} \right\} \sqrt{(F_{yw}t_f)/t_w} \]

  where \( d \) = the depth of the column section

- If the compressive force is applied at a distance less than \( d/2 \) from the member end,

  For \( N/d \leq 0.2 \),

  \[ R_n = 68t_w^2 \left\{ 1 + 3(N/d)(t_w/t_f)^{1.5} \right\} \sqrt{(F_{yw}t_f)/t_w} \]

  For \( N/d > 0.2 \),

  \[ R_n = 68t_w^2 \left\{ 1 + (4N/d - 0.2)(t_w/t_f)^{1.5} \right\} \sqrt{(F_{yw}t_f)/t_w} \]

If this limit state is exceeded, transverse stiffeners at least one-half the depth of the web are required at the application of the load and should either bear on or be welded to the loaded flange. Again, the weld should be designed to allow the unbalanced force in the stiffener to be transmitted to the web (Specifications 1993).
Compression buckling of the web occurs when compressive forces are applied at both flanges of a member in the same location. From Section K1.6 in the *Specifications*, the required strength for this limit state is:

$$\phi = 0.90$$

$$R_n = \left(\frac{1}{h}\right) 4,100 t_w^3 \sqrt{F_{yw}}$$

where $h$ is the clear distance between flanges less the fillet or corner radius. If the concentrated force near the end of the column, however, is applied (less than $d/2$ from the member end), the nominal strength $R_n$ is reduced by 50 percent. Stiffeners must be used if the limit state is exceeded and can either bear on or be welded to the loaded flange so the force can be adequately transmitted to the stiffener. In this case, the stiffeners must be designed as axially compressed members and therefore must extend the full depth of the web. The weld is designed the same.

Panel-zone web shear and sidesway web buckling, when applicable, are also limit states to be considered in determining the need for stiffeners. These limit states will not be discussed in detail here since they are not part of the study. Design provisions are provided in Sections K1.5 and K1.7 of the *Specifications*.

If stiffeners are required because a column limit state has been exceeded, AISC provides some design guidelines. The following rules are found in AISC K1.9 of the *Specifications*:

1. *The width of each stiffener plus one-half the thickness of the column web should not be less than 1/3 the width of the flange or moment connection plate delivering the concentrated force.*

2. *The thickness of the stiffeners should not be less than $t_b/2$, where $t_b = \text{thickness of beam flange or connection plate delivering the concentrated force}.*$

3. *When the concentrated force is only at one column flange, the stiffener length does not need to exceed one-half the column depth.*

Full depth stiffeners are required for cases where applied compressive forces exceed the applicable column limit states. Half depth stiffeners may be used for the other cases.
1.3 FORCE DISTRIBUTION PREDICTION

The current design model in the AISC *Manual of Steel Construction Vol. II* (Manual Vol. II 1993) assigns only the magnitude of the force that cannot be carried by the column flange or web to the stiffener. The stiffeners are therefore designed to support the difference in load between the applied force and the limiting state of the column. The Specifications are silent regarding the distribution of load between the column and stiffener. It has therefore been assumed that the stiffener does not support any of the applied load until the column has exceeded its limit state, see Figure 1.2. As stated previously, this can not follow the behavior of the connection. It is therefore advantageous to determine the distribution of force between the stiffener and column web under loaded conditions. Once this distribution is determined, an effective design approach can be developed.

The force distribution can be predicted based on the theory that at yield, the applied load is distributed over a certain distance along the column, Figure 1.5. At failure, yield lines form in a pattern extending a prescribed distance from the application of load. The column will therefore resist the applied load over the total distance, \( c \), along its length. This distance is then used to determine the effective column area. The distance, \( c \), is determined in this study through experimental testing and finite element analyses.

The distribution of load resisted by the column web and the stiffener is estimated by using the ratio of the stiffener area to the effective column web area. This ratio provides force values for the stiffener for any given applied force and assumes the stiffener resists force before the column reaches a limit state. The resisting force in the stiffener is then:

\[
P_{\text{stiff}} = \left( \frac{A_{\text{stiff}}}{A_{\text{tot}}} \right) P_{\text{applied}} \tag{1.1}
\]

where \( A_{\text{stiff}} \) = area of the stiffener cross section, \( A_{\text{tot}} \) = total equivalent column/stiffener area resisting the applied load, \( P_{\text{applied}} \) = applied load.
1.4 SCOPE OF RESEARCH

The current design model for assigning stiffener force does not follow the actual behavior of the beam-to-column connection. It assumes that the stiffener is receiving no force until the controlling limit state has been reached in the column. This assumption is inaccurate because the stiffener is a force-resisting member in the moment connection and will resist a portion of the force the instant it is applied. Research is therefore needed to determine a method for predicting the distribution of force between the column and the stiffeners. When this distribution is found, an accurate method for stiffener design can be developed. Beam and column W-shaped sections are the focus in the moment connections requiring the use of stiffeners for this research.