Educational tool for analysis of steel frames with semi-rigid connections

Christian L. Dias[1], Rafael L. Rangel[2], Luiz Fernando Martha[1]

[1]*Department of Civil and Environmental Engineering and*
Tecgraf Institute of Technical-Scientific Software Development of PUC-Rio
R. Marquês de São Vicente, 225 - Gávea, Rio de Janeiro - 22451-900 - RJ, Brazil
lfm@tecgraf.puc-rio.com, christianltdias@gmail.com
[2]*International Centre for Numerical Methods in Engineering (CIMNE)*
C. Gran Capità, S/N 08034 Barcelona, Spain
rrangel@cimne.upc.edu

Abstract. The article describes the implementation in Ftool of semi-rigid connections with nonlinear behavior of the moment-rotation relationship. The main objective is to describe the extension of the program's graphical interface and its use to demonstrate the behavior of steel frames with semi-rigid nonlinear connections. Although it is possible to couple the physical nonlinearity of the connection with geometric nonlinear analysis, the article deals only with physical nonlinearity. The semi-rigid connection is modeled using a finite element with two nodes with a stiffness matrix that relates the relative rotation between the two nodes and the moment in the connection. Nonlinear behavior is provided by multi-linear curves relating moment to rotation. The monitoring of the equilibrium trajectory of the structure with nonlinear behavior is performed in an incremental-iterative manner using several types of classical algorithms in the literature. It is also possible to show structure buckling and vibration modes considering the linear behavior of the semi-rigid connection.

Keywords: Steel frames, Nonlinear semi-rigid connections, Educational software.

1 Introduction

Joints in steel structures, in addition to connecting distinct structural elements, represent a means by which internal efforts are transmitted. These connections play a fundamental role in the structure's behavior, commonly idealized in structural analysis projects by a perfectly rigid or ideally hinged behavior. The case of a perfectly rigid connection determines that the connected elements have no freedom of rotation relative to each other, and the moment acting at the end of a beam is completely transferred to the column and connected beams. In an ideally hinged connection, there is freedom of rotation between the structural elements, with no moment being transferred between the members. However, the actual behavior of the connections between beams and columns is found in between these two extremes, in which the relative rotation between the members occurs and still exists moment transmission. This type of connection is called semi-rigid.

In general, the behavior of semi-rigid connections is non-linear, represented through curves that relate the moment with the connection's relative rotation, and its stiffness is represented by a moment vs. rotation function. Since non-linearity is associated with a structure element, it is classified as a physical non-linearity.

The incorporation of the effect of semi-rigid connections was performed in FTOOL (Martha [1]), an iterative graphics program used by students and engineers of many countries for the analysis of two-dimensional frames. The new addition took advantage of the incremental-iterative nonlinear solution methods implemented by Rangel [2], which were adapted to also consider the influence of the physical nonlinearity of semi-rigid connections, from a multilinear model to represent the behavior of the connection. The implemented semi-rigid connection model was based on the model proposed by Del Savio [3], represented by a rotational spring, which has its rigidity added to the global matrix independently. The effects related to axial and shear forces were disregarded since their deformations are much lower when compared to those generated by moments.

Dias et al. [4] presented the partial development of incorporating the physical nonlinearity of semi-rigid connections in FTOOL, detailing the implemented rotational spring model, the new interface to accommodate the connection creation and manipulation of the initial methodology adopted. The present work provides the conclusion of the development, illustrating the adaptations in the non-linear analysis process for the consideration of semi-rigid connections and some examples that validate the implemented numerical model, present in the work of Dias [5].

2 Nonlinear solution methods

2.1 Adopted numerical model

The semi-rigid connection model is represented by a rotational spring inserted at the intersection between beam elements, beam and column elements, or between column elements and supports. The rotational spring model can satisfactorily adjust the moments from the relative rotation in the semi-rigid connection. The connection is incorporated in the FTOOL as an independent finite element, presenting its own stiffness matrix added to the global stiffness matrix in the respective degrees of freedom of rotation in which it is associated. This independence implies several advantages, such as the consideration of non-linearity in the behavior of the semi-rigid connection, the possible incorporation of axial, shear, and torsion effects, and a unique methodology for any connection configuration with the element to which the connection is associated.

It should be noted that each semi-rigid connection generates a fictitious node, shared with the member to which it is associated. At the same time, the other end is connected to the global node of the structure. The fictitious node only exists in the context of analysis, and its rotation is stored at the corresponding end of the bar, following the methodology proposed by Marques et al. [6].

2.2 Incremental iterative numerical methods

Rangel [2] implemented incremental-iterative methods to solve the analysis of structures with geometric nonlinearity. In general, the non-linear solution is discretized in a series of load increments that seek to approximate the non-linear response of the structure. Each incremental step is further divided into smaller calculations, representing a cycle of iterative corrections to eliminate the residual forces of the incremental step. This iterative cycle is repeated until reaching a convergence criterion, determined by a tolerance determined by the user.

In each incremental-iterative step, the tangent stiffness matrix is obtained to calculate the nodal displacements in the current step. The internal forces are also calculated in a process that repeats until the convergence of the result. The non-linear solution methods were adapted to consider the physical non-linearity of the semi-rigid connection, its stiffness being updated in each step of the non-linear solution, added to the global tangent stiffness matrix of the structure.

2.3 Adaptation for physical nonlinearity of semi-rigid connections

The behavior of the semi-rigid connection is modeled from the multilinear method, in which the pairs of points of the moment vs. rotation curve of the connection are informed by the user. Figure 1 illustrates the straight lines formed by the pairs of inserted points, which are used directly to obtain the tangent stiffness of the semi-rigid connection and the internal moments from its relative rotation for each incremental-iterative step.

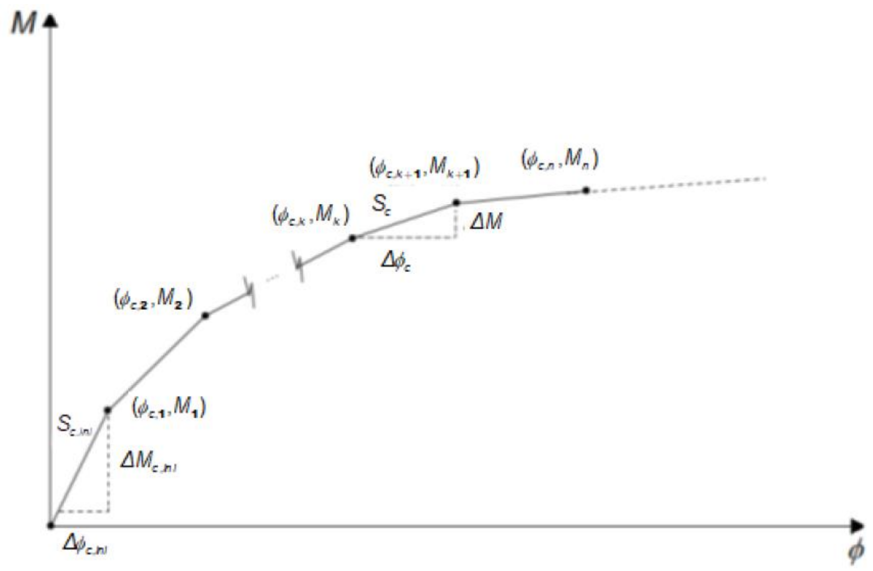


Figure 1: Multilinear model to represent the nonlinear behavior of semi-rigid connections

In each nonlinear solution step, the relative rotation obtained for the semi-rigid connection is used as a parameter to determine the corresponding straight segment of the multilinear curve, with the slope of the segment being equal to the tangent stiffness of the connection. Eq. 1 illustrates two possible situations for calculating the stiffness of the connection from the moment vs. rotation curve.

$$\begin{cases} S_c = \frac{M_{k+1}-M_k}{\emptyset_{c,k+1}-\emptyset_{c,k}} & \emptyset_{c,k} \leq \emptyset_{c,rel} < \emptyset_{c,k+1} \\ S_c = \frac{M_n-M_{n-1}}{\emptyset_{c,n}-\emptyset_{c,n-1}} & \emptyset_{c,rel} \geq \emptyset_{c,k+1} \end{cases} \tag{1}$$

The first case illustrates the calculation when the given relative rotation is within the range of points informed by the user. The second relation represents the calculation when the relative rotation is beyond the last point entered. In this case, the stiffness of the connection will be equal to the inclination of the last straight segment, which extends infinitely.

Obtaining the bending moment in the connection is calculated respecting the same relations as in Eq. 1, its value being equal to the interpolation of the straight line, in the first case, and equal to the value of the bending moment in the last point if the rotation is beyond the points entered by the user.

3 Nonlinear analyses

Nonlinear analyses were performed considering the physical nonlinearity of semi-rigid connections. It is noteworthy that the FTOOL allows performing analyses also considering linear semi-rigid connections. The Load Control Method was chosen in the analyzed cases, and the tolerance value for solution convergence was equal to 10^{-5}. The structure's tangent stiffness matrix is calculated in each incremental-iterative step, with the load increment being adjusted during analysis since the FTOOL allows the visualization of the deformed configuration and internal forces, in addition to the alteration of the analysis parameters in each solution step. Other solution methods are present in FTOOL's non-linear analysis options, including methods that can follow the solution trajectory in the structure's post-critical regime, which is not the case in the examples presented.

3.1 Two-story frame - Chan e Chui [7]

This analysis is based on an experimental study considered by Chan and Chui [7]. It is a two-story frame with non-linear semi-rigid connections inserted in the intersection between beams and columns. Both beams and columns were discretized into 10 elements for analysis, and 4 different types of connections were considered:

Single web angle, top and seat angle, flush-end plate, and extended endplate. The results were also compared in totally rigid connections, considering one case with fixed supports and the other with hinged supports.

The structure has a length equal to 6.1 m and a total height of 7.32 m, divided into two floors. The material modulus of elasticity is equal to 200 GPa. Profiles of types W360x72 and W310x143 were considered for beams and columns, respectively. Vertical loads of module P are applied at the ends of the beams, while horizontal loads introduce destabilizing effects on the frame, representing 2% of the load P on the first floor and 1% on the second floor. For each type of connection, the imported moment vs. rotation curves define the physical non-linear behavior of the semi-rigid connection.

Figure 2 illustrates the FTOOL interface with the semi-rigid connections definition menu activated, illustrating the properties and definitions of a connection type (single web angle). The discretized model used in the nonlinear geometric analysis is also illustrated, considering the physical nonlinearity of the semi-rigid connections.

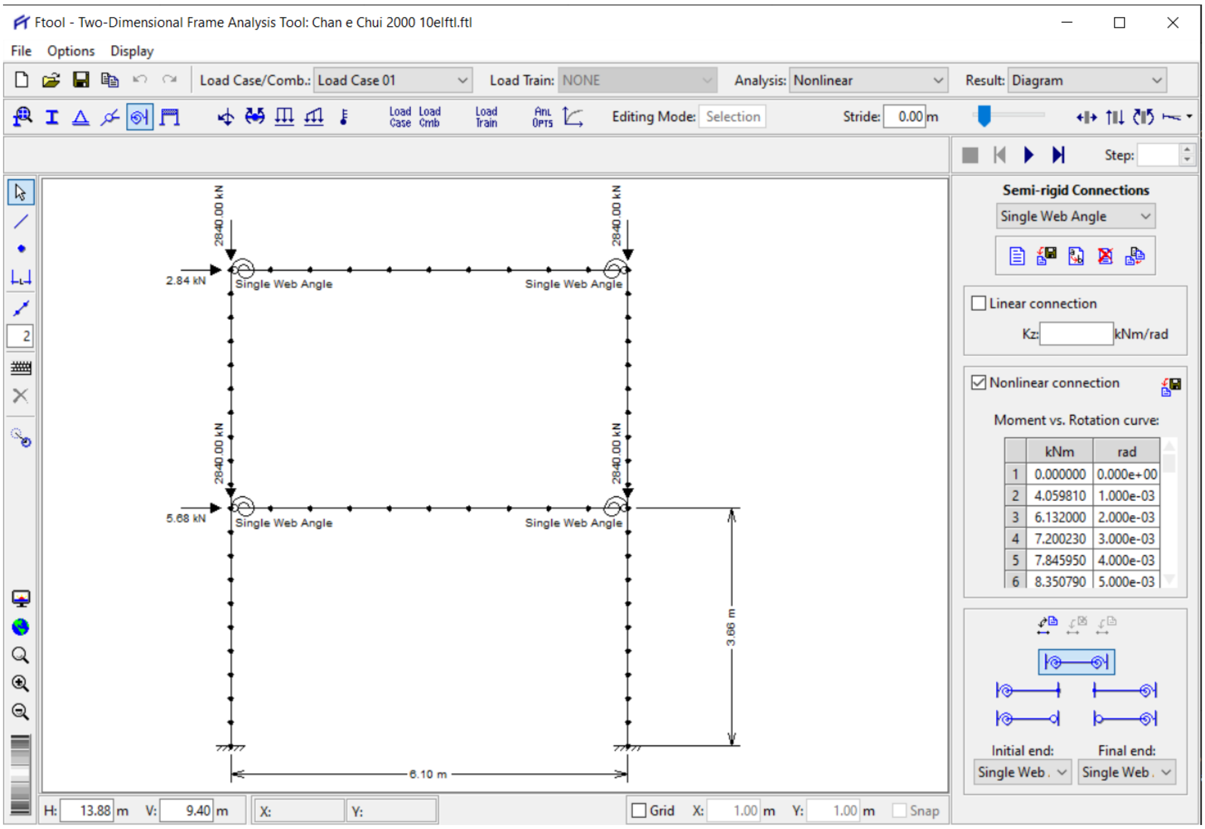
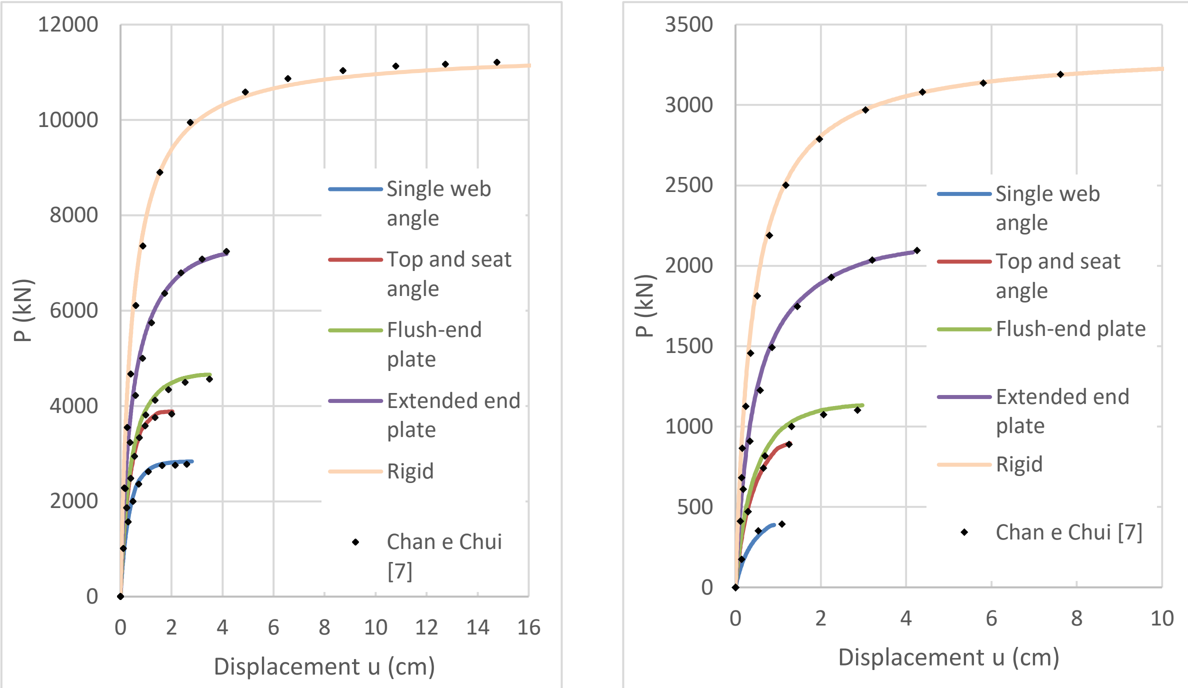


Figure 2: Analyzed model in the first example and semi-rigid connections menu, showing the single web angle connection definitions

Figure 3 illustrates the comparison of the results obtained in the analysis with the values presented in the study by Chan and Chui [7], considering both fixed and labeled supports for each type of semi-rigid connection adopted in the analysis. From the results, it is possible to identify the effect of semi-rigid connections on the behavior of the structure. In the case of more flexible connections, there is a considerable reduction in the critical load of the structure, while more rigid connections increase its value. The convergence of the results with the values provided by Chan and Chui [7] becomes evident, accommodating in a very satisfactory way the effect of the physical nonlinearity of the connections in all analyzed cases for any type of semi-rigid connection considered in the analysis.



Fixed support

Labeled support

Figure 3: Comparison of first analysis results with data provided by Chan e Chui [7] for each connection

3.2 Two-story frame - Stelmack et al. [8]

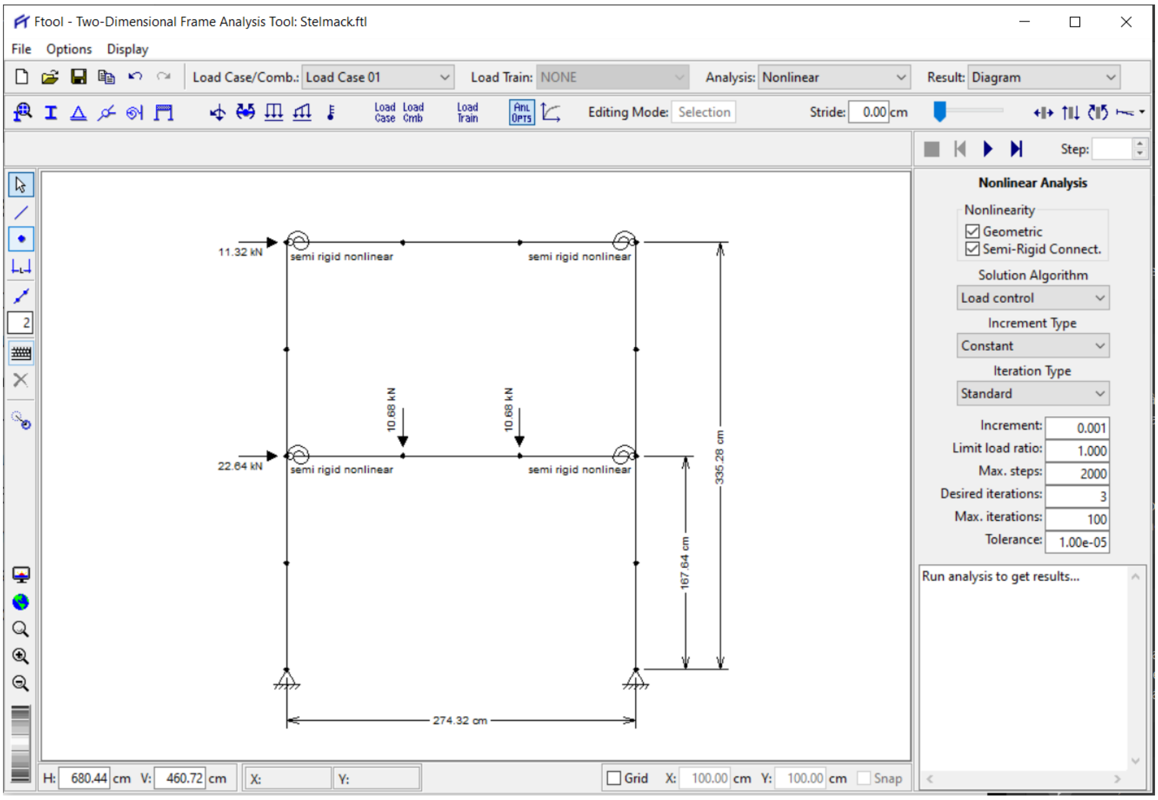


Figure 4: Analyzed model of the second example and the nonlinear analysis menu showing the analysis parameters

This example is part of a study proposed by Stelmack et al. [8], which presents experimental results in a non-linear geometric analysis with non-linear semi-rigid connections. Figure 4 illustrates the two-story portico used for the analysis. The frame refers to an A36 steel material with semi-rigid non-linear connections between the beams and columns. All elements were built using the W5x16 profile. Fixed loads of 10.68 kN are present on the beam of the first floor of the structure, equally spaced. Two incremental loads were applied on the side of the frame, with a value of 2P and P for the first and second floors, respectively.

For the nonlinear behavior of the semi-rigid connection, the points of the moment vs. rotation curve were inserted, also reported by Stelmack et al. [8]. Figure 5 illustrates the graphic comparison between the results obtained in FTOOL with those provided by Stelmack et al. [8], and also with the results found in the work of Lemes [9].

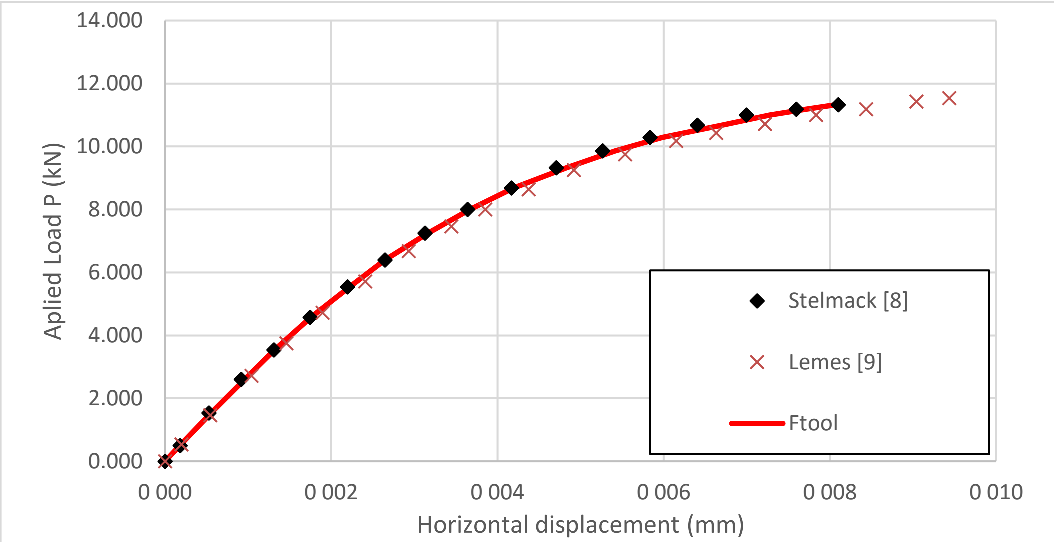


Figure 5: Comparison of analysis results with experimental data provided by Stelmack et al. [8] and Lemes [9]

The results obtained showed great agreement with the experimental values provided by Stelmack et al. [8], proving the efficiency of the semi-rigid connection model adopted and other adaptations. As seen in Figure 5, the results also show excellent convergence when compared with the data provided by Lemes [9].

4 Conclusions

Incorporating the influence of semi-rigid connections in the FTOOL guarantees the tool a high potential for advanced analysis of two-dimensional frames. As an independent finite element, the rotational spring model presents a simple implementation, which guarantees very satisfactory results in the representation of semi-rigid connections. Furthermore, the numerical model adopted allows for the direct insertion of the non-linear behavior of the connection, in addition to opening space for future works that consider the coupling of axial, shear, and torsional rigidities.

The adaptation of the nonlinear solution methods proved to be very efficient, presenting results very close to those found in the literature, demonstrating the quality of the methodology adopted for the solution. The new implementation followed the FTOOL philosophy, maintaining ease of use with the software's user-friendly interface. Thus, it is expected that the addition of semi-rigid connections in the new version of the program will be of immense value to students and engineers seeking to carry out an advanced structural analysis.

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