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Ftool version 5: What are the new features

Luiz F. Martha[1], Rodrigo B. Burgos[2], Rafael L. Rangel[3], Guilherme C. G. Barros[4], Evandro Parente Junior[5]

[1]*Dept. of Civil and Environmental Engineering, Pontifical Catholic University of Rio de Janeiro (PUC-Rio)*
Rua Marques de São Vicente 225, Gávea, 22451-900, Rio de Janeiro/RJ, Brazil
lfm@tecgraf.puc-rio.br
[2]*Dept. of Structures and Foundations, State University of Rio de Janeiro (UERJ)*
Rua São Francisco Xavier 524, 20550-900, Rio de Janeiro/RJ, Brazil
rburgos@eng.uerj.br
[3]*Faculty of Engineering Technology, University of Twente*
Drienerlolaan 5, 7522 NB, Enschede, Netherlands
r.rangel@utwente.nl
[4]*Centre for Geotechnical Science and Engineering, The University of Newcastle*
University Drive, Callaghan NSW 2308
guilherme.barros@newcastle.edu.au
[5]*Department of Structural Engineering and Civil Construction, Federal University of Ceará*
Campus do Pici, Bloco 733, 60440-900, Fortaleza, Ceará, Brazil
evandro@ufc.br

Abstract. This work presents a new version of Ftool, a program for structural analysis of two-dimensional frame models, widely used by Civil Engineers and students. The new features of this version are: second-order geometric non-linear analysis using the two-cycle method, stability and natural vibration analyses through an eigenvalue problem, semi-rigid connections with moment-rotation linear-elastic behavior, and consideration of structural deformation constraints, such as inextensible and rigid members, using Lagrange multipliers. This latest version, like the previous ones, has no incremental-iterative step-by-step analysis, i.e., it has only direct solving methods without specification of increment parameters, such as load ratio, maximum number of steps, or tolerance values.

Keywords: two-cycle analysis, stability analysis, natural vibration analysis, semi-rigid connections, structural deformation constraints.

1 Introduction

Ftool (Two-dimensional Frame Analysis Tool) is an interactive graphical program for the structural analysis of planar frames. Its primary objective is the simple and efficient prototyping of structures. Its creation began in the 1990s at the Tecgraf Institute of Technical-Scientific Software Development of PUC-Rio (Tecgraf/PUC-Rio – https://www.tecgraf.puc-rio.br). The program was initially developed for classroom use at PUC-Rio, but has evolved into a tool widely used in professional structural projects across the world. The program is available on its website – www.ftool.com.br – and the technical manual is available at https://www.tecgraf.puc-rio.br/ftool.

In the 2022 edition of CILAMCE, Martha and Rangel [1] presented an article on the history of the development of Ftool. The reader is directed to that article to understand how the development of Ftool took place and how it continues to evolve. That article highlights the improvements achieved in each version over the years and demonstrates the reach of the program's user community.

The program uses the C programming language with an object-oriented programming discipline. Ftool's internal data representation is based on the Half-Edge Data (HED), a topological data structure originally developed to represent polyhedral surfaces [2]. At Tecgraf, it has been implemented in a general-purpose function library for handling planar subdivisions [3]. This data structure is a crucial feature of Ftool, providing robust and

efficient modeling capabilities.

Ftool's basic edition allows users to define models efficiently and directly. It analyzes the structural model and provides various results, such as internal force diagrams, deformed configuration, influence lines at any point along the members, and result envelopes for live loads. Cross sections can be defined parametrically according to various models (rectangular, T-, L-, and I-shaped profiles, etc.) by selecting from a wide variety of standard shapes (AISC, Gerdau, etc.), or generically by defining the section's geometric properties such as area and moment of inertia. Structural members can be analyzed using Euler-Bernoulli or Timoshenko theory. Supports can be rigid or elastic, inclined, and subject to imposed displacements. Ftool's robust and user-friendly modeling capabilities enable the creation of various types of structures, from the simplest to the most complex, in just minutes.

The current version of the Ftool Advanced Edition adds several features to facilitate its educational and professional use. A key feature of the Advanced Version is the ability to support multiple load cases. This feature is crucial in structural design, as a real structure must often withstand numerous loads, such as accidental loads, winds from various directions, etc. The Ftool Advanced Edition can analyze all these cases directly. It is also possible to create weighted load combinations and view the result envelopes for all load cases and load combinations, presenting simple and worst-case scenarios for each element in a given structure.

This paper presents a new version of Ftool (version 5.00). The new features of this version, available in the advanced edition, are: second-order geometric non-linear analysis using the two-cycle method, eigenvalue buckling analysis, natural vibration mode eigenvalue analysis, semi-rigid connections with moment-rotation linear-elastic behavior, and consideration of structural member deformation constraints, such as inextensible and rigid members, using Lagrange multipliers. For theory details on these developments, see [4–12].

2 New features of Ftool version 5.00

Fig. 1 shows the graphical interface of version 5.00 of Ftool's advanced edition. The following sections briefly present the improvements in this new version, indicating related articles.

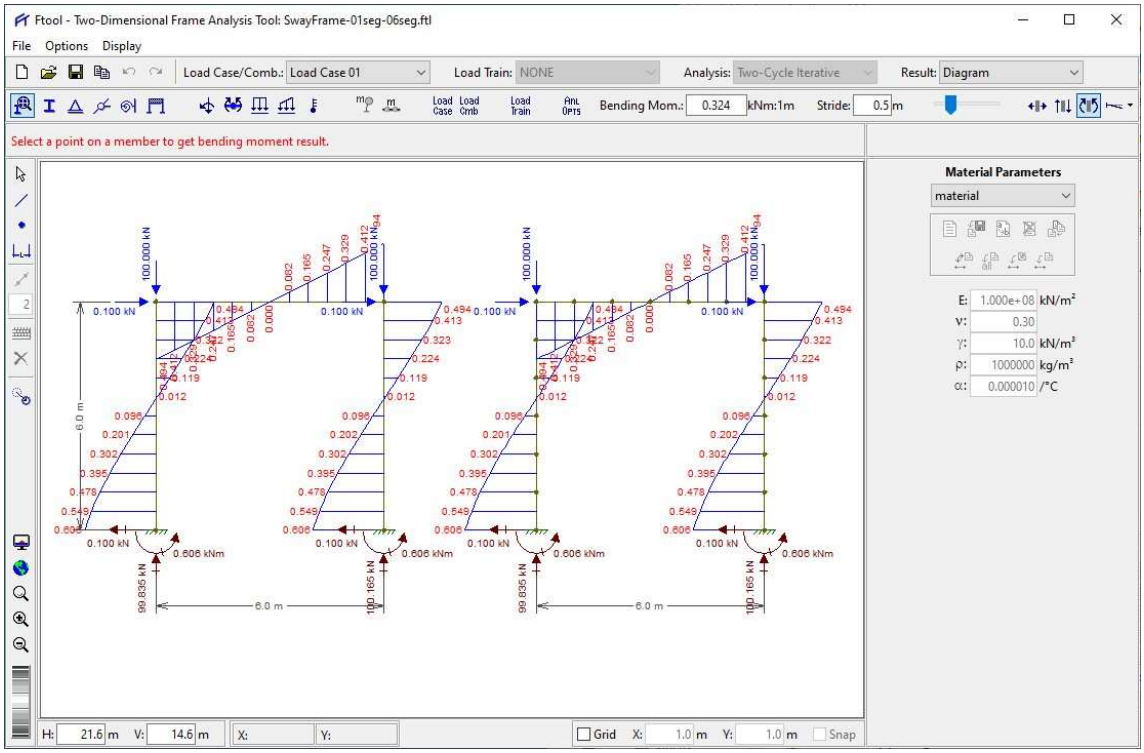


Figure 1. Graphical interface of version 5.00 of Ftool's advanced edition

2.1 Second-order geometric non-linear analysis using the two-cycle method

The two-cycle iterative method [13] uses the equilibrium equation of the structural problem in two stages. The equilibrium equation matrix uses the elastic stiffness matrix in the first cycle. This matrix is calculated without considering any second-order effects. In the second cycle, to include the effects of geometric nonlinearity, the stiffness matrices of each frame member must be updated by adding a geometric stiffness matrix, which depends on the element internal forces. These forces are determined based on the nodal displacements and rotations calculated in the first cycle.

Ftool was adapted to perform two-cycle analyses, with Fig. 2 showing the selection of this solution method in the graphical interface. To solve the structural model, the program employs frame elements based on solutions of the differential equations obtained from the deformed configuration [4, 5]. The results of displacements and rotations for the examples studied in the cited articles are identical to the analytical solutions, showing that combining the two-cycle method with the exact element formulation is promising and can diminish the need for discretization and the use of complicated nonlinear solution algorithms. An example is shown in Fig. 1, where the members of the left frame are not discretized, while the members of the right frame are subdivided into six segments. It can be seen that the bending moment diagrams of the two frames are practically identical.



Figure 2. Drop-down list for selection of analysis type, indicating the selection of the two-cycle iterative analysis

2.2 Stability analysis

The stability analysis provides the structure's critical loads and corresponding buckling modes [14, 15]. Fig. 3 shows Ftool's graphical interface with the first buckling mode of a simple frame [6].

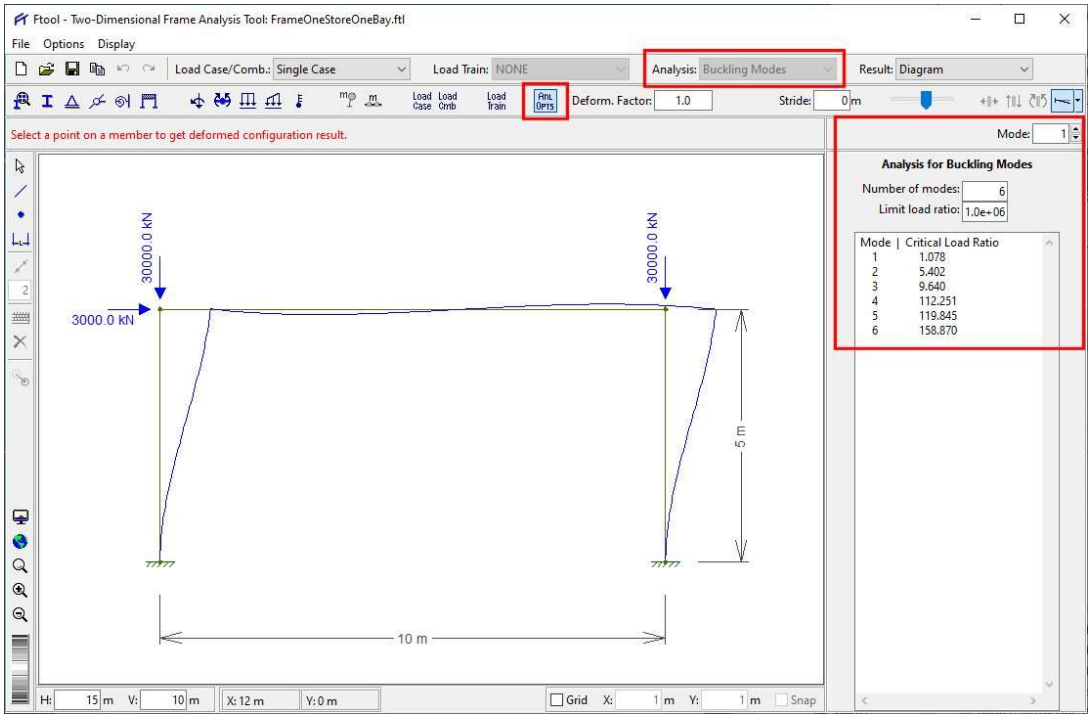


Figure 3. An example of stability analysis in Ftool showing a frame buckling mode and all critical load ratios

In Fig.3, the "Analysis" drop-down list shows the selection of Buckling Modes analysis. The "AnlOpts" button displays the "Analysis for Buckling Modes" menu on the right side. The user may select the desired buckling mode to be displayed on the main canvas. In addition, the value of the critical load ratio for each buckling mode is provided in table format in the right-side menu.

2.3 Natural vibration analysis

The natural vibration analysis provides the structure's natural frequencies, vibration modes, mode participation factors, and mode effective masses [15–17]. In version 5.00 of Ftool, two mass attributes were created: concentrated nodal masses and uniformly distributed member masses. The button for selecting the concentrated nodal mass attribute and its menu are indicated in Fig. 4. Translational and rotational masses may be applied to the nodes of the structural model. Fig. 5 shows the selection of the distributed member mass button and its attribute menu. It is possible to activate self-weight mass and apply additional distributed mass on a member.

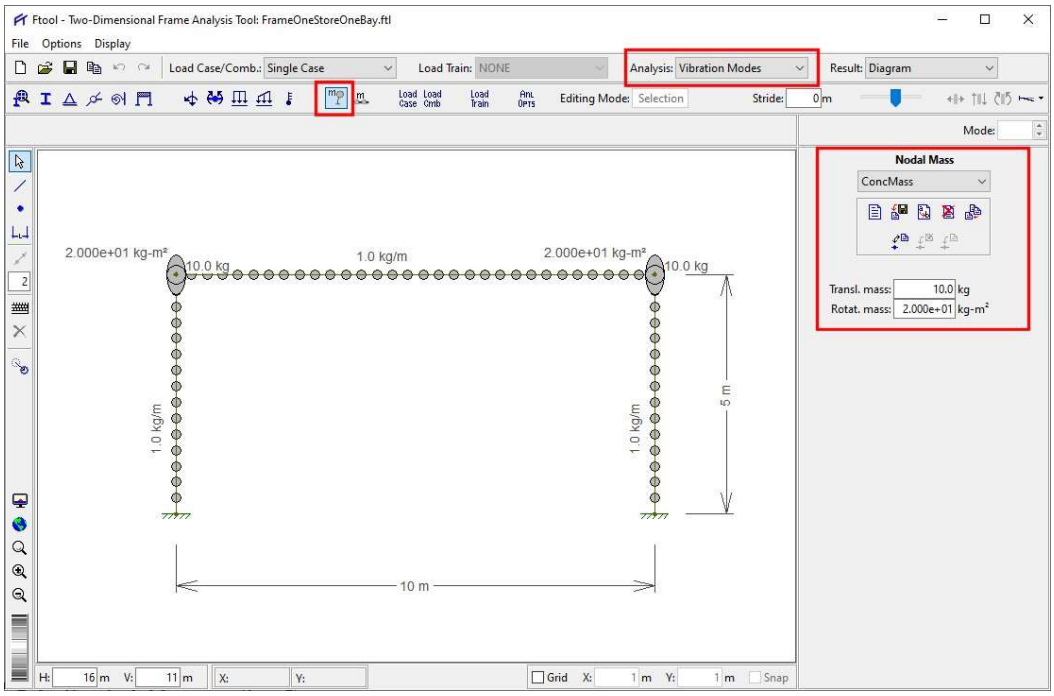


Figure 4. Concentrated nodal mass (translational and rotational) attribute used in vibration mode analysis

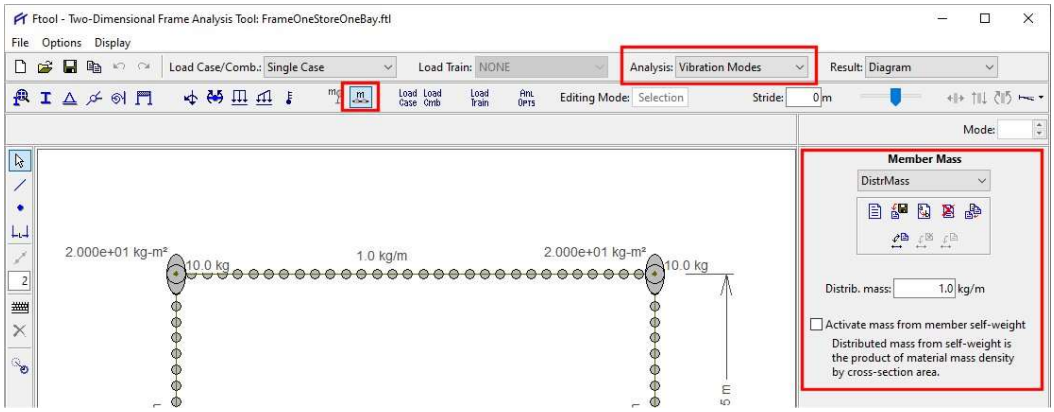


Figure 5. Distributed member mass attribute used in vibration mode analysis

Fig. 6 shows the first vibration mode of the frame model depicted in Figs. 4 and 5, along with a list of the computed frequency and period of each vibration mode [6]. The right-side menu of "Analysis for Vibration Modes" also provides an option to select the type of mass matrix: consistent or lumped nodal mass [18–21].

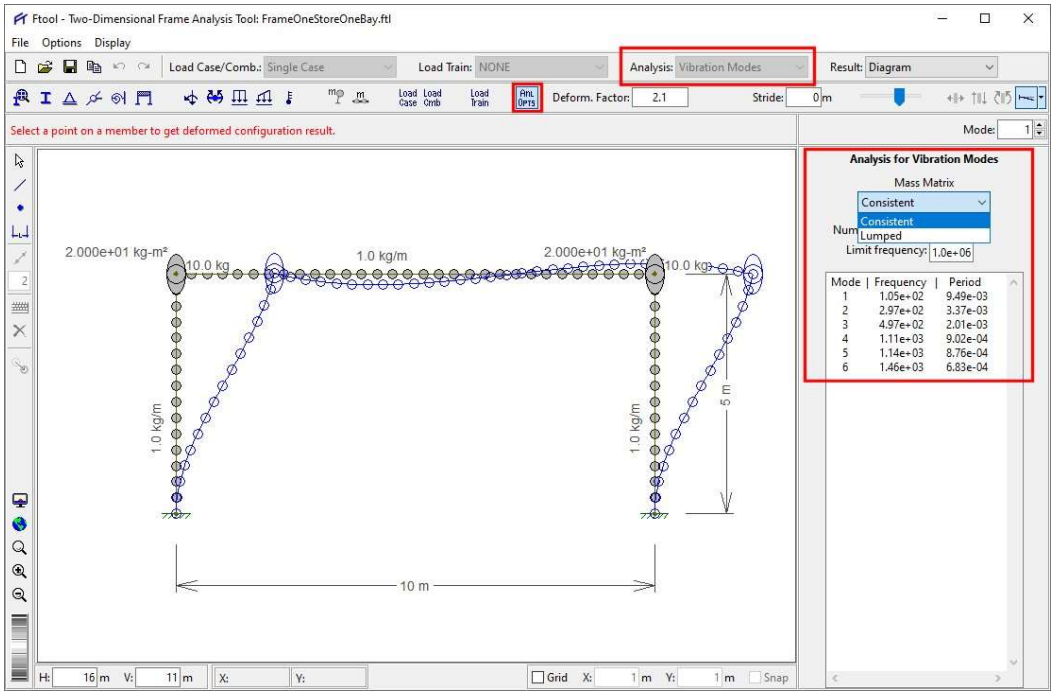


Figure 6. Natural vibration analysis showing the first vibration mode of the frame from Figs. 4 and 5

2.4 Semi-rigid connections

A semi-rigid connection is modeled in Ftool using a finite element with two nodes, considering a stiffness matrix that relates the relative rotation between the two nodes and the moment in the connection [7–10]. As shown in Fig. 7, a rotational spring element is created with a fictitious node at each semi-rigid connection of a beam element. This fictitious node has an additional rotational degree of freedom, and its translational degrees of freedom are shared with the structure node. The fictitious node connects the beam element to the spring element.

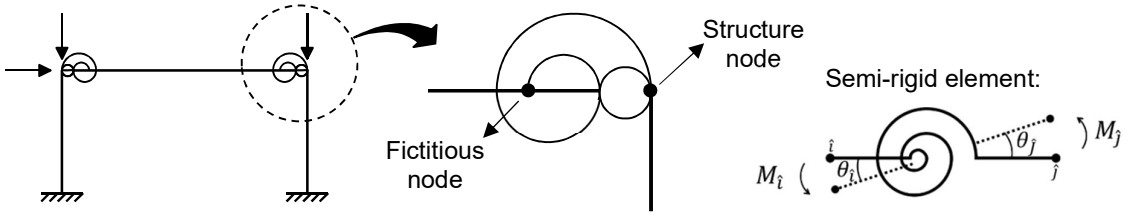


Figure 7. Semi-rigid connection modeled as an isolated rotational spring element

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

Fig. 8 shows Ftool's graphical interface with the deformed configuration of a frame with two semi-rigid connections at the beam ends, as well as the menu for creating and applying linear-elastic semi-rigid connections.

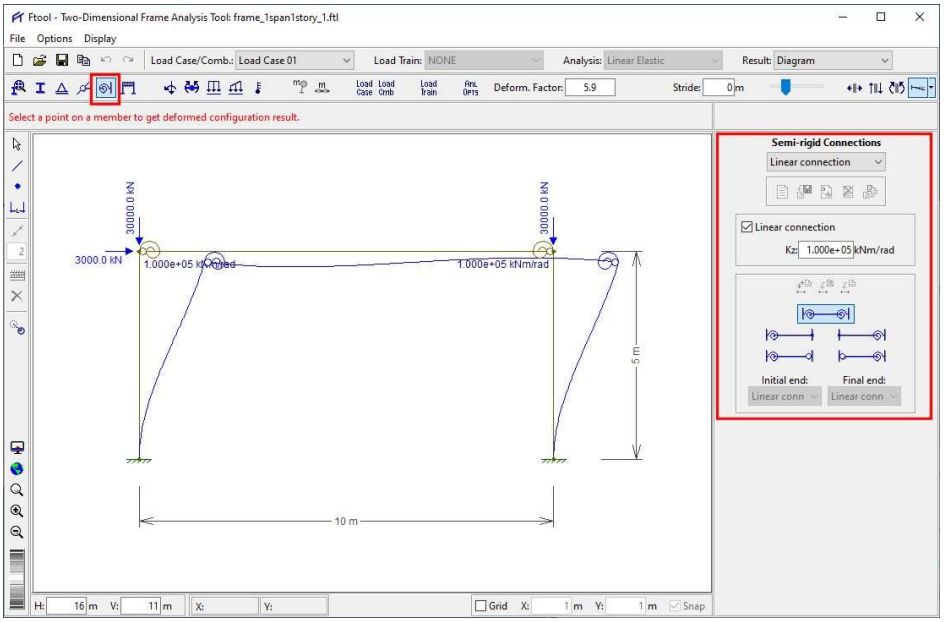


Figure 8. Deformed configuration of a frame with two semi-rigid connections, and Semi-rigid Connections menu

2.5 Member deformation constraints

Rigid and inextensible members are useful in educational software, as they capture the essence of the structural behavior with fewer variables. In addition, they allow a comparison with results obtained by hand calculation using classical structural analysis methods. Therefore, Ftool, as an educational software, considers the analysis of frame structures with inextensible and rigid members, i.e., members without axial and bending strains.

There are three main approaches to handling constraints: transformation, penalty function, and Lagrange multiplier methods [22–24]. The transformation methods, also known as master-slave elimination, use each constraint to eliminate one equilibrium equation, reducing the number of degrees of freedom. However, this approach does not allow the determination of axial forces in inextensible members or bending moments in rigid members. Implementing the penalty function method is trivial, since, physically, it corresponds to assigning a very large value to the axial stiffness (EA) of inextensible members and a considerably large value to the bending stiffness (EI) of rigid members. The previous versions of Ftool used the penalty function method. However, as the penalty factor increases, the stiffness matrix becomes increasingly ill-conditioned, leading to significant solution errors. In fact, some users have reported spurious responses of frames with deformation constraints in Ftool.

The methodology adopted in the new version of Ftool for considering member deformation constraints uses Lagrange multipliers [11, 12], which eliminates the aforementioned problem. It adds strain constraints to the total potential energy minimization, leading to a quadratic programming problem. In addition, this approach is very suitable for computational implementation because it does not affect the generic characteristic of a matrix structural analysis. The solution gives rise to one Lagrange multiplier per constraint, essential for computing member internal forces. However, there are situations in which inextensible and rigid member constraints may be redundant, which prevents the determination of dependent Lagrange multipliers. In these cases, it is impossible to determine the members' internal forces with redundant constraints. The solution adopted in Ftool to this problem is to find an optimal solution for member internal forces by minimizing the difference between the constrained and the unconstrained model.

Fig. 9 shows Ftool's graphical interface with the model of a building with rigid beams (shear building), and the menu for applying member deformation constraints. Flexible members may be extensible or inextensible, with the latter presenting no axial deformation. In addition, shear deformation may be constrained (Bernoulli beam – default case) or unconstrained (Timoshenko beam). A rigid member has no deformation. A new feature in Ftool is to specify a rigid member as a rigid link. The difference between a rigid member and a rigid link is that no diagram of internal forces is displayed for rigid link members.

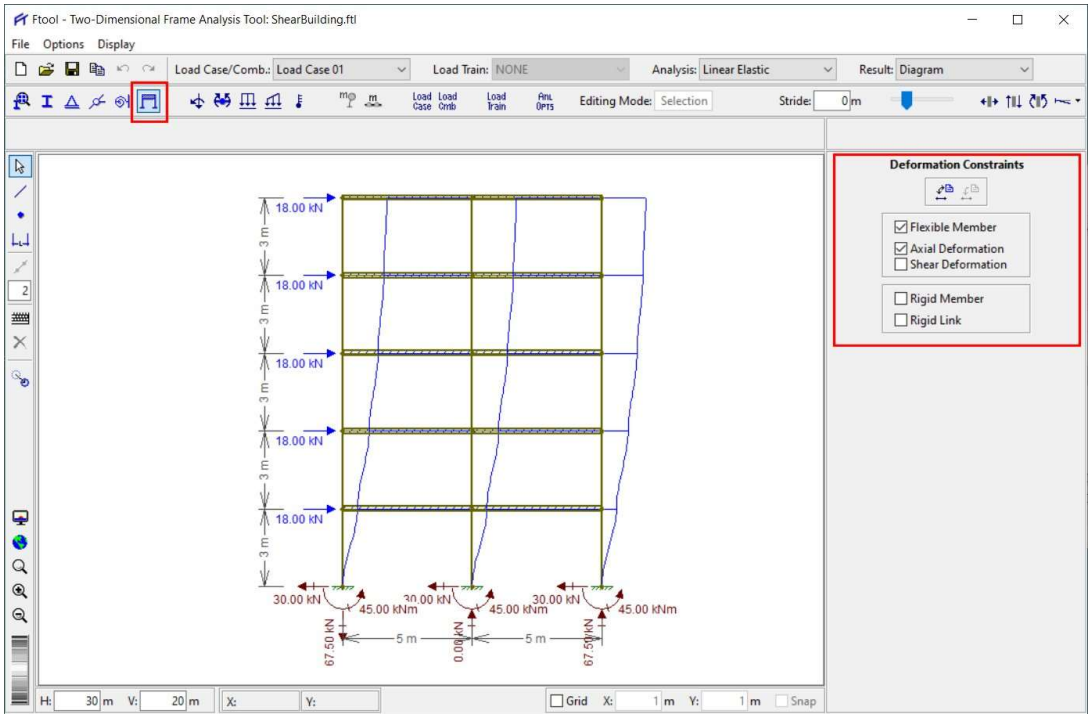


Figure 9. Deformed configuration of a frame with rigid beams, and Deformation Constraints menu

3 Conclusions and Future Developments

Ftool is an interactive graphical system designed to provide engineering students with an academic tool. It does not focus on advanced numerical simulations. Instead, it integrates a user-friendly interface for efficient creation and manipulation of planar frame models (pre-processing), fast solution process, and rapid and effective visualization of results (post-processing) in a platform for teaching structural behavior.

We believe that none of the available commercial finite element programs, such as SAP2000, ABAQUS, or ROBOT, offer the same level of integration between pre- and post-processing, ease of use, modeling capabilities, and versatility in visualizing results for plane frames as Ftool does. None of these programs was designed as an academic tool. Their data structures were primarily designed to implement the numerical analysis tasks of a finite element program. Designing a fully integrated educational interactive graphical software requires a well-structured data representation scheme that supports modeling, the numerical analysis aspects, and result visualization, all within a single user interface. Ftool has demonstrated all of these features, as frequently reported to its creator by civil engineering professors from various universities in Brazil and abroad. Furthermore, its user-friendliness and rapid and simple prototyping of structural behavior explain why many engineering companies also use Ftool.

The improvements introduced in the new version, as presented in this article, are expected to have a significant impact both on teaching structural analysis and on professional activities in Structural Engineering, benefiting the entire Ftool user community.

Future versions of Ftool are already under development [25–28]. They focus on incremental-iterative solution methods to enable the discovery of the structure's equilibrium paths in post-critical geometric nonlinear analyses and when considering semi-rigid connections with nonlinear behavior.

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References

[1] L. F. Martha and R. L. Rangel, "FTOOL: Three decades of success as an educational program for structural analysis". *Proceedings of the XLIII Ibero-Latin American Congress on Computational Methods in Engineering (CILAMCE 2022), Foz do Iguaçu/PR, Brazil, November 21-25, 2022*.
[2] M. Mäntylä. *An Introduction to Solid Modeling*. Computer Science Press, 1988.
[3] P. R. Cavalcanti, P. C. P. Carvalho, and L. F. Martha, "Non-manifold modeling: An approach based on spatial subdivision". *Computer-Aided Design*, vol. 29, n. 3, pp. 209–220, 1997.
[4] R. B. Burgos, L. F. Martha, M. A. C. Rodrigues, and R. L. Rangel, "Modelling of the P-δ effect using interpolating functions". *Proceedings of the joint XLII Ibero-Latin American Congress on Computational Methods in Engineering and III Pan-American Congress on Computational Mechanics (CILAMCE-PANACM 2021), Online, November 9–12, 2021*.
[5] R. B. Burgos and L. Encarnação Silva, "Evaluation of the P-Δ (P-Delta) effect in columns and frames using the two-cycle method based on the solution of the beam-column differential equation". *MethodsX*, vol. 11, 2023.
[6] R. L. Rangel and L. F. Martha, "Ftool 5.0: Nonlinear, stability and natural vibration analyses". *Proceedings of the XLI Ibero-Latin American Congress on Computational Methods in Engineering (CILAMCE 2020), Online, November 16-19, 2020*.
[7] C. L. Dias, R. L. Rangel, and L. F. Martha. "Educational tool for analysis of steel frames with semi-rigid connections", *Proceedings of the joint XLII Ibero-Latin American Congress on Computational Methods in Engineering and III Pan-American Congress on Computational Mechanics (CILAMCE-PANACM 2021), Online, November 9–12, 2021.*
[8] C. L. Dias, R. L. Rangel, and L. F. Martha. "Nonlinear analysis in FTOOL with semi-rigid connections: a partial development", *Proceedings of the XLI Ibero-Latin American Congress on Computational Methods in Engineering (CILAMCE 2020), Online, November 16-19, 2020*.
[9] I. R. Marques, P. C. F. Lopes, R. L. Rangel, and L. F. Martha, "Implementação de conexão semirrígida em modelos reticulados no contexto da programação orientada a objetos", *Proceedings of the XL Ibero-Latin American Congress on Computational Methods in Engineering (CILAMCE 2019), Natal/RN, Brazil, November 11–14, 2019*.
[10] C. L. Dias. *Analysis of steel structures with semi-rigid connections using the educational software FTOOL*. MSc Thesis, Pontifical Catholic University of Rio de Janeiro (PUC-Rio), 2021.
[11] G. C. G. Barros, E. Parente Jr, and L. F. Martha. "Consideration of structural member deformation constraints using Lagrange multipliers". *Proceedings of the 6th International Conference on Engineering Optimization*, Springer, 2019.
[12] G. C. G. Barros. *Stress recovery in the Finite Element Method considering linearly dependent strain constraints*. PhD Thesis, Pontifical Catholic University of Rio de Janeiro (PUC-Rio), 2019.
[13] W. F. Chen and E.M. Lui. *Stability Design of Steel Frames*. CRC Press, 1991.
[14] W. McGuire, R. H. Gallagher, and R. D. Ziemian. *Matrix Structural Analysis, 2nd Edition*. Faculty Books, 2000.
[15] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery. *Numerical Recipes: The Art of Scientific Computing, 3rd Edition*. Cambridge University Press, 2007.
[16] R. W. Clough and J. Penzien. *Dynamics of Structures*, *3rd Edition*. Computers & Structures, Inc, 2003.
[17] M. Paz and W. Leigh. *Structural Dynamics: Theory and Computation, 5th Edition*. Kluwer Academic Publishers, 2004.
[18] C.H.B. Resende, P.C. Lopes, R.L. Rangel, L.F.P. Muñoz, and L.F. Martha, "An educational GUI-based software for dynamic analysis of framed structural models". *International Journal of Computer Applications in Technology*, vol. 16, no. 7, pp. 265–286, 2023.
[19] L.F. Martha, C.H.B. Resende, P.C. Lopes, and R.L. Rangel, "LESM: An interactive-graphics open-source educational software in MATLAB for static and dynamic structural analysis". *Proceedings of the XLIV Ibero-Latin American Congress on Computational Methods in Engineering (CILAMCE 2023)*, Porto, Portugal, November 13–16, 2023.
[20] P.C. Lopes, R.L. Rangel, and L.F. Martha, "Extensão de programa gráfico para análise de vibrações de modelos estruturais reticulados". *Proceedings of the XL Ibero-Latin American Congress on Computational Methods in Engineering (CILAMCE 2019)*, Natal/RN, Brazil, November 11–14, 2019.
[21] P.C. Lopes, R.L. Rangel, and L.F. Martha, "Development of a graphical application for the dynamic analysis of linear elements structural models". *Proceedings of the 25th International Congress of Mechanical Engineering (COBEM 2019)*, Uberlândia/MG, Brazil, October 20–25, 2019.
[22] O. C. Zienkiewicz, R. L. Taylor, and J. Z. Zhu. *The Finite Element Method: Its Basis and Fundamentals*, 2013.
[23] R. D. Cook, D. S. Malkus, M. E. Plesha, and R. J. W. Witt. *Concept and Applications of Finite Element Analysis*, 2002.
[24] C. A. Felippa, *Introduction to Finite Element Methods*, 2017.
[25] R. L. Rangel. *Educational tool for structural analysis of plane frame models with geometric nonlinearity*. MSc Thesis, Pontifical Catholic University of Rio de Janeiro (PUC-Rio), 2019.
[26] R.L. Rangel and L.F. Martha, "Programa para análise geometricamente não linear de pórticos por meio de um controle extensivo do usuário". *Proceedings of the XL Ibero-Latin American Congress on Computational Methods in Engineering (CILAMCE 2019)*, Natal/RN, Brazil, November 11–14, 2019.
[27] R.L. Rangel and L.F. Martha, "Implementation of a user-controlled structural analysis module with geometric nonlinearity". *Proceedings of the 25th International Congress of Mechanical Engineering (COBEM 2019)*, Uberlândia/MG, Brazil, October 20–25, 2019.
[28] R.L. Rangel and L.F. Martha, "Educational tool for the analysis of structures with geometric nonlinearity". *Proceedings of the* XXXIX Ibero-Latin American Congress on Computational Methods in Engineering (CILAMCE 2018), Paris/Compiegne, France, November 11–14, 2018, pp. 472–473.