

FTOOL: Three decades of success as an educational program for structural analysis

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Abstract. This article describes the history of the development of the educational program FTOOL, which is a user-friendly software used all over the world for teaching structural analysis of two-dimensional frames as well as for engineering projects. The paper highlights the main milestones in the evolution of the program since its creation in 1992. It reports how the main features of the program were progressively incorporated, through the contribution of several academic works, until reaching the current state. The focus is given to the experience of using FTOOL as a powerful educational tool in many structures' disciplines of a Civil Engineering undergraduate course. It also presents the program's latest improvements and the new features that are coming in the next versions. These new implementations include buckling modes for stability analysis, vibration modes, geometrically nonlinear analysis, semi-rigid connections with linear and non-linear behavior, and reinforced concrete design. With these developments, the program will remain up-to-date with the engineering demands of nowadays.

Keywords: structural analysis, frame structures, educational software, interactive graphics analysis.

1 Introduction

FTOOL (Two-dimensional Frame Analysis Tool) is an interactive graphics program for structural analysis of plane frames. It has as its primary objective the simple and efficient prototyping of structures. The program was created by the first author of this article and was initially developed for classroom use, but it has evolved into a tool frequently used in professional structural projects. The program is available through its website – www.ftool.com.br – and the technical manual is available on the website <https://www.tecgraf.puc-rio.br/ftool>.

The program is implemented using the C programming language with an object-oriented programming discipline. The internal data representation of FTOOL is based on the topological data structure HED (Half-Edge Data structure), initially devised for representing polyhedral boundaries [1], which was implemented in a generic usage function library for handling planar subdivisions [2] in the Tecgraf Institute (Technical-Scientific Software Development Institute) of PUC-Rio. This data structure is a crucial characteristic of FTOOL, which allows for a robust and efficient modeling capability.

FTOOL's basic edition allows the user to define models efficiently and straightforwardly. It analyzes the structural model and offers many different results, such as internal force diagrams and the structure deformed configuration, as well as influence lines for any point on the structure and load-train result envelopes. Cross-sections may be defined either parametrically according to multiple templates (rectangular, T-, L- and I-shapes, etc.), by selecting from a diverse array of standard shapes (AISC, Gerdau, etc.), or generically (defining the section's geometric properties such as area and moment of inertia). Structural members may be analyzed by either Euler-Bernoulli or Timoshenko theory. Supports may be either rigid or elastic and may be inclined or suffer imposed displacements. The robust and friendly modeling capabilities of FTOOL allow multiple types of structures, from the simplest to the most complex, to be modeled in a matter of minutes.

The advanced edition of FTOOL adds a few functionalities to facilitate its educational and professional use. An essential feature of the advanced version is multiple load cases. This characteristic is fundamental in structural design, as an actual structure must generally resist multiple loadings, such as live loads, wind from various directions, etc. FTOOL's advanced edition is able to analyze all these cases directly. It is also possible to create weighted load combinations and visualize the result envelopes for both load cases and load combinations, presenting simple and worst-case scenarios for each element in a given structure.

This article describes the evolution of FTOOL over the last 30 years and how it has become a successful program for teaching structural analysis of frames in undergraduate engineering courses. In section 2, it presents a historical overview of the various versions of the software since its creation in 1992. Section 3 describes the experience of using FTOOL as an educational tool. Section 4 summarizes the program's latest improvements and the new features coming in the next versions. Finally, Section 5 draws some conclusions about the development of FTOOL and its educational use.

2 Historical overview¹

The FTOOL program was initially developed as an integrated research project coordinated by Professor Marcelo Gattass of the Department of Informatics of PUC-Rio and director of PUC-Rio's Tecgraf Institute, with funds received from CNPq (National Council of Technological and Scientific Development). The responsibility for FTOOL is, since the beginning, in the hands of its author Professor Luiz Fernando Martha of the Department of Civil and Environmental Engineering of PUC-Rio. Former undergraduate students Eduardo Thadeu Leite Corseuil, Vinícius Samu de Figueiredo, and Adriane Cavalieri Barbosa from PUC-Rio's Civil Engineering Department contributed to the development of the program as research assistants from March 1991 to December 1992. The program was initially developed on a DOS platform and underwent several improvements until April 1995. Figure 1 shows the pre- and post-processing screens of DOS **version 1.01** (1992–1998).

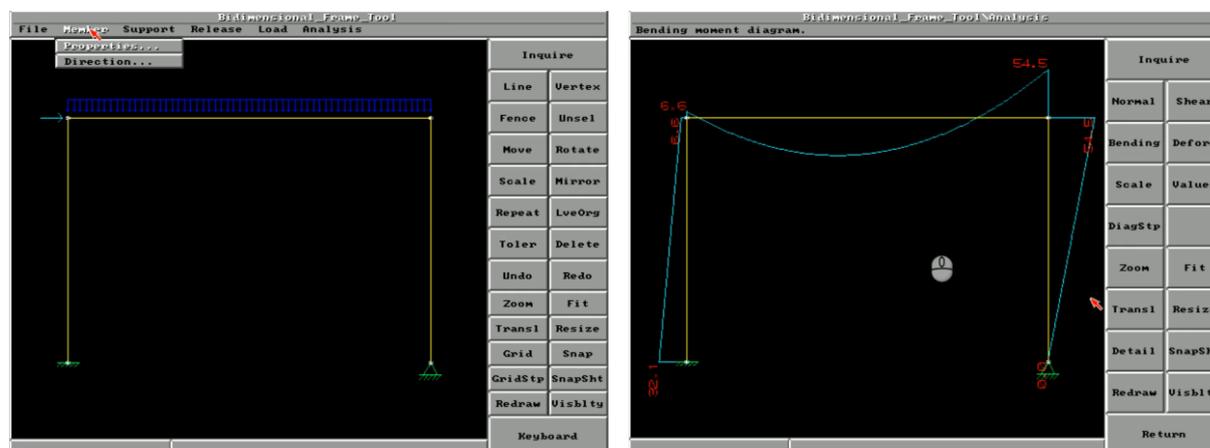


Figure 1. Pre- and post-processing screens of DOS version 1.01 of FTOOL (1992–1998)

Waldemar Celes Filho, Professor in the Department of Informatics of PUC-Rio, developed the HED function library that is the internal data structure of FTOOL. The program's numeric analysis module received a contribution from the former Ph.D. student of PUC-Rio, Ivan Fábio Menezes, who is currently a Professor in the Department of Mechanical Engineering of PUC-Rio.

From 1997 to 1998, FTOOL was revised by Professor Martha, who used the IUP user-interface system and the CD graphics system, both developed by Tecgraf/PUC-Rio. These graphics systems allowed the program to be executed on Windows and Unix. In February 1998, **version 2.00** was launched. Successive versions were then introduced, each one with new improvements. Figure 2 shows the pre- and post-processing screens of Windows **version 2.05** (June 1999).

¹ There is a channel on YouTube with a series of videos that describe the history of FTOOL: <https://www.youtube.com/playlist?list=PLMNpxcy0KqYVP-9B1On-aAtAKqowzFA26>

Version 2.06 was launched in April 2000 with the following main features:

- Created units and number formatting configuration for all the analysis parameters. There are pre-defined options to set default SI units (International System), default US units (United States System), or all units in kilonewtons and meters.
- Replaced Member Properties menu by Material Parameters menu and Section Properties menu, which handles geometric parameters of cross-sections. Created default Concrete and Steel material parameters.
- Created spring supports (translation and rotation springs).
- Created options to display load and reaction values in addition to the load and reaction drawings.
- Created an option to display loads together with the response diagrams and deformed configuration.
- Modified info message box to use multi-line texts instead of just passive label texts as in the previous versions. This allows the user to copy the info message to the clipboard and paste it into a text editor.

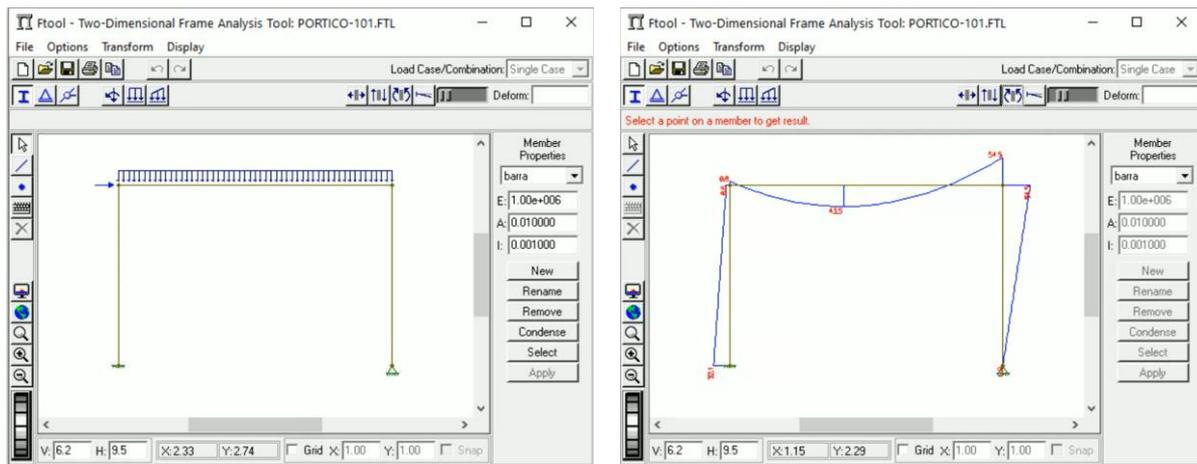


Figure 2. Pre- and post-processing screens of version 2.05 of FTOOL (Jun/1999)

In August 2000, **version 2.08** was also launched for the Linux platform, including the following features:

- Created dimension lines for distance annotation on the structure image.
- Created member temperature variation loading. The user specifies a temperature variation at the top edge of the cross-section (edge at the positive local y-axis side) and a temperature variation at the bottom of the cross-section (edge at the negative local y-axis side). A new material parameter, the thermal expansion coefficient, and two additional cross-section properties, the cross-section depth and the center of gravity height, were added to support this capability.
- Modified the program to allow the creation of attributes (material parameters and cross-section properties) and loads prior to creating a structure. In this way, the user may keep a file with the attributes and loads that are often used, as well as units and number formatting, and use this file as a starting point for creating a new structure.

In **version 2.09** (January 2001), specific procedures to aid the educational use of FTOOL for structural analysis were incorporated: inextensible and infinitely rigid members and member-end moments. In **version 2.10** (November 2001), influence lines were added and, in **version 2.11** (August 2002), other improvements such as more general definition of beam member cross-sections were included. Several types of cross-sections were made available, each one defined by specific parameters. Two I-shape section tables were incorporated (Brazilian specifications). This version also added the ability to import model attributes from other files, an option to define the member side (tension or compression) to draw bending moment diagrams, and an option to draw result values transversal to the members.

In **version 2.12** (February 2008), a menu was added to create and manipulate generic load trains, with variable numbers of concentrated and distributed loads (full and empty cars), and external and internal live loads. Since that version, as shown in Fig. 3, the critical positions of load trains are displayed along with influence lines with an option to exhibit internal force envelopes (minimum and maximum values of internal forces) due to moving load trains. The determination of critical load train positions that produce minimum and maximum values of an

internal force in a cross-section constitutes an optimization problem. However, there is no analytical expression that describes the variation of a given internal force as a function of the load train position, which makes it impossible to use most classical optimization methods, as these methods require, in most cases, the use of at least the first derivative of the objective function with respect to design variables. Therefore, the algorithm adopted in FTOOL for determining critical load train positions that minimize and maximize internal forces in a cross-section is based on an evolutionary strategy, which is a probabilistic method. This work was developed in the M.Sc. dissertation of Gisele Holtz [3], advised by Luiz Eloy Vaz and Luiz Fernando Martha, and has been published in three congresses [4-6].

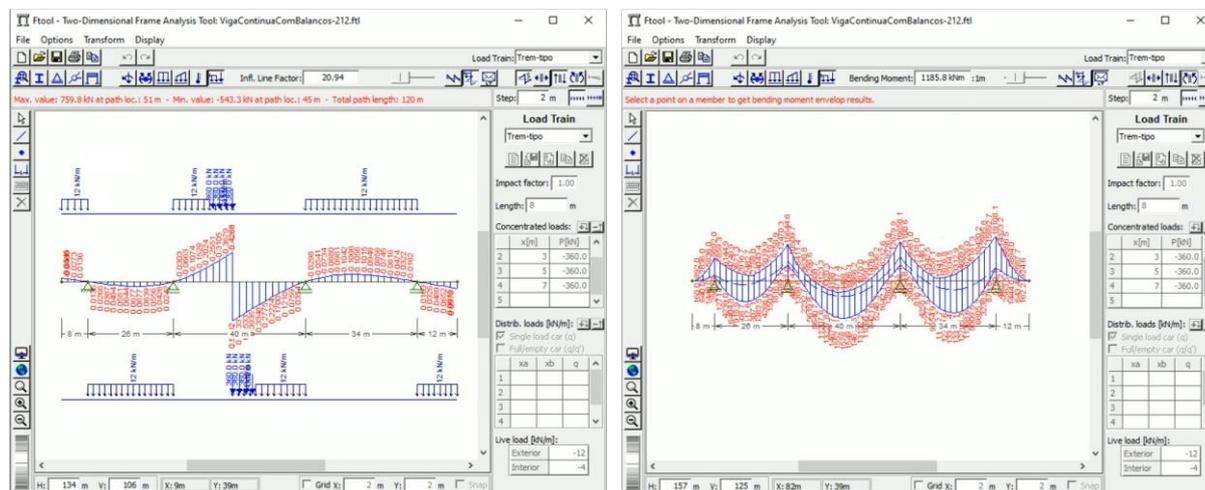


Figure 3. Screens of version 2.12 (February 2008): Influence line with load train critical positions and bending moment envelopes for moving load train

In **version 3.00**, launched in August 2012, the IUP graphics interface was updated to reflect evolutions in native interfaces of Windows and Linux. The interface of the Linux version had a considerable improvement as it adopted the GTK package. Among other developments is the consideration of shear deformations in the bending of members (Timoshenko beams). Another significant improvement was the elimination of the auxiliary file (extension ".pos") used to link the program with its analysis module (solver). This file may still be saved, but the user must explicitly demand it.

Version 3.01 was partially funded by Mills® Estruturas e Serviços de Engenharia S.A., a scaffolding engineering company. In this version, launched in August 2015, the interface for object transformations was modified so that users could choose to perform transformations that maintain the topology of the structure while displaying static results and influence lines, which are dynamically updated. Cross-section shape tables from Vallourec and Mills were also included.

FTOOL went through a profound transformation in **version 4.00**. The development of the program was transferred to ALIS Engineering and Systems Solutions and subsequently transferred to Marlin Ltda. An advanced edition for professional use, with a commercial license, was developed. The objective of the advanced edition is to supply structural design needs. Commercialization of the advanced edition is exclusively oriented toward developing new functionalities, which was not possible solely by the individual work of the program's author. One should note that the free distribution of the basic edition of FTOOL still continue.

In version 4.00, whose interface is shown in Fig. 4, the deformed configuration of the structure can be displayed with or without values in the global (vertical and horizontal) or local (transversal and axial) coordinate systems. Multiple keyboard shortcuts have been added to control the program, allowing for more efficient manipulation of the model by more experienced users. The advanced edition enables the creation of multiple load cases and weighted load case combinations, as well as the visualization of result envelopes for load cases and combinations. This edition also includes generic prismatic cross-sections created by the composition of trapezoids, unlike those cross-section shapes already supplied by the program. Finally, this edition allows the customization of the program's initialization, in which the user can define the units and number formats to be used and multiple visualization parameters, among other options.

The primary motivation for creating the advanced version with a commercial license was to fund the development of FTOOL. Up to version 3.00, the program was essentially developed by its creator alone. The support from Mills provided funding for additional programmers, and it was clear that a professional attitude was necessary. One has to consider that the number of users of FTOOL had grown to the order of half a million, not only in Brazil but also in many other countries. Figure 5 shows a graph of the evolution of the number of downloads of the FTOOL executable file (Windows and Linux) from June 1999 to October 2015, obtained solely from the public download area of Tecgraf WWW server. The blue curve indicates the monthly volume of downloads according to the scale of the left vertical axis, and the orange and green curves provide, respectively, the total volume of downloads accumulated and per version according to the scale of the right vertical axis. The number of downloads may be even higher since many other websites copied and distributed the program executable. It is interesting to observe from the green curve that each time a new version of FTOOL was launched (black vertical lines), its number of downloads increased faster than the previous version.

However, the experience with the commercial license of FTOOL was partially successful. Funding from this source is not sufficient to support a minimal team of programmers. For this reason, the development of FTOOL continues to happen at a slow pace. In recent years, there have been many improvements in the program made by the first and second authors of this article, which are described in Section 4, but some adjustments have to be made to finalize a new version. Other sources of funding from companies interested in supporting this educational project are under negotiation.

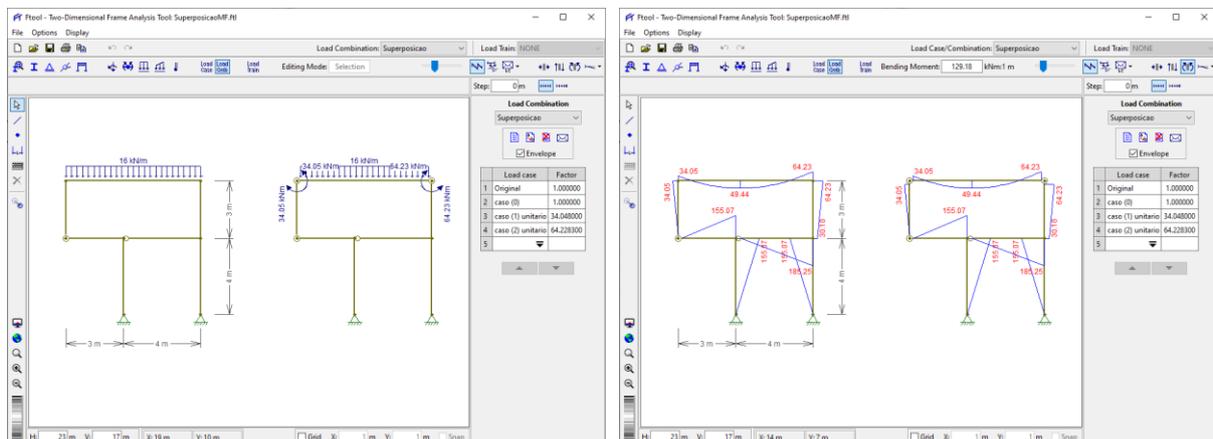


Figure 4. Pre- and post-processing screens of the load combination feature of version 4.00 (June 2017)

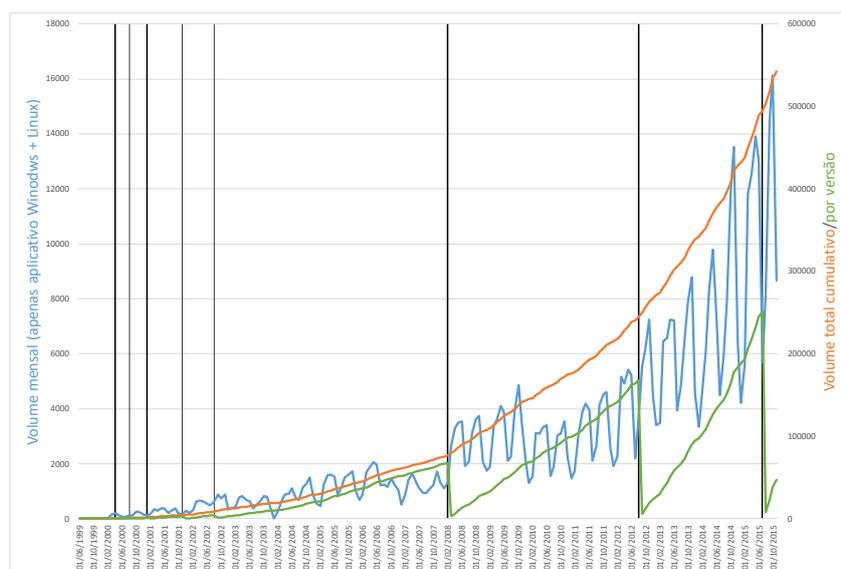


Figure 5. Number of downloads of the executable file of FTOOL from 1999 to 2015

3 FTOOL as an educational tool

Understanding the behavior of frame structures requires a great deal of experience and expertise in structural analysis and design. Civil engineering students expend most of their effort in structural analysis classes learning the theoretical aspects of existing analysis methods. Typically, students will only understand the actual behavior of frame structures entirely later in the design classes of the engineering course. Not rarely, this knowledge is acquired after they graduate, during their professional activities. However, our experience has been that the process of learning structural analysis methods without the knowledge of the structural behavior is not efficient. In fact, it is challenging to motivate the average student to learn the theory behind the analysis methods without understanding how the analyzed model behaves in practice. Therefore, the learning of analysis methods improves significantly when the student can learn the structural behavior simultaneously.

Several computer programs for structural analysis of frames exist and are available for academic purposes. Three excellent examples are MASTAN2 [7,8], INSANE [9], and LESM [10-18]. Nevertheless, we believe that there is a lack of academic tools concerned with teaching the model's behavior. FTOOL is an interactive graphics system whose primary purpose is to provide a structural engineering student with such an academic tool. This tool, however, is not focused on the numerical techniques of a frame structure analysis, an important academic area that also needs to be addressed. Classical references for numerical matrix structural analysis are, for example, the books of McGuire et al. [7]; Przemieniecki [19]; Weaver and Gere [20]; Felton and Nelson [21]; and Martha [22]. Instead, this program relies on integrating a friendly user interface, an efficient frame model creation and manipulation (pre-processing), a fast and transparent numerical analysis, and a fast and effective visualization of analysis results (post-processing) as a platform for teaching bidimensional frame structure behavior.

We also believe that none of the available standard finite element codes, such as SAP2000 [23], ABAQUS [24], or ROBOT [25], presents the degree of integration across pre-processing, numerical analysis, and post-processing phases, the ease of usage, the modeling capabilities, and the versatility of frame result visualization as the system described in this work. This is so because none of those programs were designed as academic tools. The data structures of those systems were mainly devised for implementing the numerical analysis tasks of a finite element code. In the design of a fully integrated educational, interactive graphics software, one has to develop a well-designed data representation scheme that allows for not only the numerical analysis aspects of the simulation but also the modeling and result visualization aspects, all in one seemingly user interface. FTOOL has proven to have all these characteristics, as reported to the program's creator on numerous occasions by civil engineering professors from many universities in Brazil and other countries, and confirmed by the graph in Fig. 5.

There is no space here to show examples of using FTOOL for teaching structural behavior. Only one example is discussed, a simple frame in two versions (statically determinate and indeterminate) with three loading cases: a uniform force, temperature variation, and a prescribed displacement (Fig. 6). The structural models are shown on the left image and the bending moment diagrams are given on the right. The results demonstrate that despite statically determinate structures present displacements for all loading cases (not displayed herein), temperature variations and prescribed displacements do not produce bending moments, or any other internal force, in this type of structure. On the other hand, all loading cases produce internal forces in the statically indeterminate model.

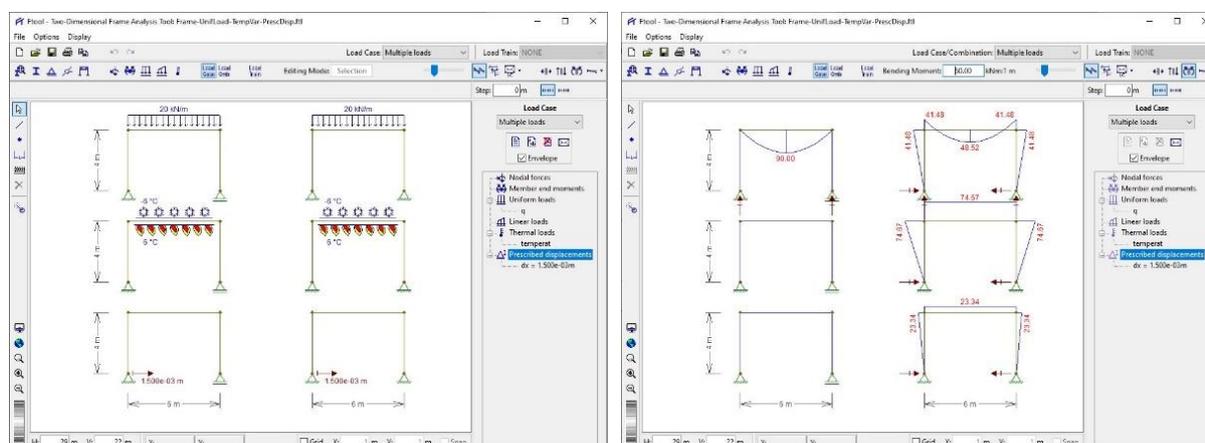


Figure 6. Difference of behavior between statically determinate and indeterminate structures

4 Future versions

One of the reasons for the correct and robust behavior of FTOOL is the quality control for releasing new versions. This attitude has been the standard procedure since the beginning of the program's development. For this reason, version releases are so spaced out in time. This attitude is also the reason why several new functionalities developed by the research group at the Tecgraf Institute of PUC-Rio have not yet been made available in the distribution version. These new features present a high level of sophistication and result from a series of master's dissertations guided by the creator of the program. This section summarizes the new features that will be available in future versions and lists the dissertations and related articles already published. The Reference section in the sequel contains links to all the referred works. The new functionalities of FTOOL may be divided into five topics:

- Stability analysis by computing buckling modes and critical loads.
- Vibration analysis by computing natural vibration modes and frequencies.
- Geometrically nonlinear analysis by considering large displacements and rotations.
- Physically nonlinear analysis by considering semi-rigid connections with nonlinear behavior.
- Reinforced concrete design.

The future features of FTOOL related to the first three topics are based on the dissertations of Rodrigo Burgos [26] and Rafael Rangel [27]. Some articles describing the implementation and usage of these features have been published in conference proceedings [28-31]. The dissertations of Alexandre Del Savio [32] and Christian Dias [33] are the basis of the new functionalities related to nonlinear analysis with semi-rigid connections. Other references for the implementation of this type of analysis in FTOOL are also available [34-36]. Regarding reinforced concrete design, the future capabilities of FTOOL come from the dissertations of Luís Fernando Kaeyer [37], Christiana Niskier [38], Maria Flavia Silva [39], and Bárbara Gomes [40]. The following articles related to the development of this functionality have been published: [41-46].

5 Conclusions

This article has summarized the development of the structural analysis software FTOOL since its creation in 1992. It was demonstrated that the program is the result of several academic projects supervised by its creator, in addition to some more recent tasks funded by the industry or the commercialization of an advanced version. The paper has also pointed out some aspects of the experience of using FTOOL as an educational tool. The success of the program for this purpose is reflected in the enormous number of users spread across various countries over the past three decades. This is a consequence of coordinated and organized developments guided by the quality control of new implementations. Such developments are always focused on the concept of educational software, aiming at the ease of use of the graphical interface and improvements that meet the needs of engineering students.

The new features that have already been implemented for future versions were also listed. They will allow the program to remain up-to-date with the engineering demands of nowadays. Moreover, the implementation of structural analysis of grillage models is also planned as a future work, which would require the graphical interface of FTOOL to be updated for 3D visualization. However, since these implementations are very sophisticated, future releases will take some time to be available to the general public. Even with additional funding from the aforementioned sources, the creator of FTOOL does not intend to change the pace of development. The main reason is that FTOOL is not a commercial program, but solely an educational and research environment.

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