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FORMWORKS-PLUS: IMPROVED PRE-PROCESSOR FOR VECTOR ANALYSIS SOFTWARE

V. Sadeghian¹, F.J. Vecchio²

¹ PhD Student in the Department of Civil Engineering at the University of Toronto, Toronto, ON, Canada

² Professor of Civil Engineering at the University of Toronto, Toronto, ON, Canada

Abstract: VecTor is a public-domain suite of computer programs developed for nonlinear finite element analysis of reinforced concrete. A graphics-based pre-processor (FormWorks) was developed for 2D concrete membrane structures, greatly contributing to the software's utility and success. However, modeling other types of structures within VecTor is a time consuming process, requiring manual definition of the finite element mesh, loads and analysis parameters in standard text files. A user-friendly pre-processor is required for the entire suite of programs if they are to be of greater use to design engineers. The first objective of this study was to develop an updated version of FormWorks (FormWorks 3.7) which will be more user-friendly and compatible with the improvements made in VecTor2 over the past ten years. It is mainly developed to model the different types of materials now available in VecTor2 including reinforced concrete, structural steel, masonry, wood, concrete-steel laminates, concrete-SFRC laminates, masonry-SFRC laminates, and others. The second objective was to create an extended version of FormWorks (FormWorks-Plus) for use with the remaining VecTor programs. The extended version is capable of modeling different types of structures including 2D membrane structures, 3D solid structures, shell structures, plane frames, and axisymmetric solid structures. FormWorks-Plus has a wide range of viewing features, and facilities for specification of node coordinates, elements, loads and material properties.

1 Introduction

Satisfying performance-based design codes, designing complex infrastructures, and analyzing structural behavior under extreme load conditions all have combined to create a need for nonlinear finite element programs to analyze reinforced concrete structures. The VecTor^(c) suite of programs has been developed at the University of Toronto to analyze different types of structures such as beams (VecTor1), 2D membrane structures (VecTor2), 3D solid structures (VecTor3), plates and shells (VecTor4), plane frames (VecTor5), and axisymmetric solids (VecTor6). Several experimental programs with different types of specimens have been undertaken at the University of Toronto and elsewhere to verify the accuracy of the programs. In addition, analyzing real-world structures including frames, slabs, shear walls, silos, bridges, offshore platforms, crash barriers and nuclear containment structures have demonstrated the value of the VecTor programs in determining the complex nonlinear behaviour of concrete structures.

A user-friendly pre-processor is required for the entire suite of programs if they are to be of greater use to design engineers. A pre-processor would aid in creating appropriate structural models, inputting and checking data, selecting proper analysis parameters, and specifying appropriate loads. In addition, its graphing capabilities would allow the user to see the structure from different views, cut various sections and permit a wide range of plots to demonstrate the structure shape, material specifications and applied loads. A graphics-based pre-processor (FormWorks) was developed for program VecTor2 by Peter Wong

(2002), greatly contributing to the software's utility and success. However, the remaining VecTor programs do not have pre-processors and they run in a DOS environment from Fortran executable files; standard text editors are used to create input data files.

2 Background Information

The FormWorks program was written in the C++ programming language using Microsoft Foundation Classes, and compiled with Microsoft Visual C++ Version 6.0. Windows programming with Visual C++ is built base on the Microsoft Foundation Classes (MFC). These classes represent an object-oriented approach which is a method of using "objects" – data structures consisting of data fields and methods together with their interactions – to design applications and computer programs. The process of writing a Windows program involves creating and using MFC objects, or objects of classes derived from MFC. The objects of these classes use member functions for communicating with Windows, for processing Windows messages, and for sending messages to each other. These derived classes, of course, inherit all of the members of their base classes. These inherited functions do practically all of the general routine work necessary for a Windows application to work.

The structure of the FormWorks application consist of two main classes — a document and a view. A set of data in the window application is called a document. Standard mechanisms are provided within MFC for managing data in a document. These mechanisms are inherited by the document class from the base class defined in the MFC library, so one gets a broad range of functionality built-in to the application automatically, without having to write any code. A view is an object that provides a mechanism for displaying some or all of the data stored in a document. It defines how the data are to be displayed in a window and how the user can interact with them (Horton, 2008).

The Document/View structure of the FormWorks application contains instances of several major classes: CJobData, CStructureData, CLoadData, CAttributeData and CWMultiPolygon. Each of these classes contains instances of smaller classes or utilizes them in data structures. Additionally, the CPr1Doc class contains the Serialize() member function to save data. The view class CPr1View, among other purposes, contains functions for drawing to the screen, printing and interacting with the mouse. The flow chart in Figure 1 summarizes the program structure.

The method that FormWorks source code uses to store and retrieve data is called serialization. It is the process of writing or reading an object to or from a persistent storage medium. The basic idea of serialization is that an object should be able to write its current state, usually indicated by the value of its member variables, to persistent storage. Later, the object can be re-created by reading, or deserializing, the object's state from the storage.

To run a VecTor analysis, four input files are required: Job File, Auxiliary File, Structure File, and Load File. Figure 2 shows how FormWorks generates input files for the VecTor programs. The extension of the files depends on the type of VecTor program that is going to be used for analysis.

3 Material Types

In the last 10 years, several new types of materials have been added to VecTor2. As the main program developed, there was a need to update its pre-processor. A new version of FormWorks, FormWorks 3.7, was developed to support the recently added features of VecTor2 in the last decade.

Reinforced concrete materials in FormWorks include concrete materials, as well as other materials, that are modeled with or without smeared reinforcement components or laminate components. Figure 3 shows the **Define Reinforced Concrete Materials** window which allows user to add, modify or delete reinforced concrete material types.

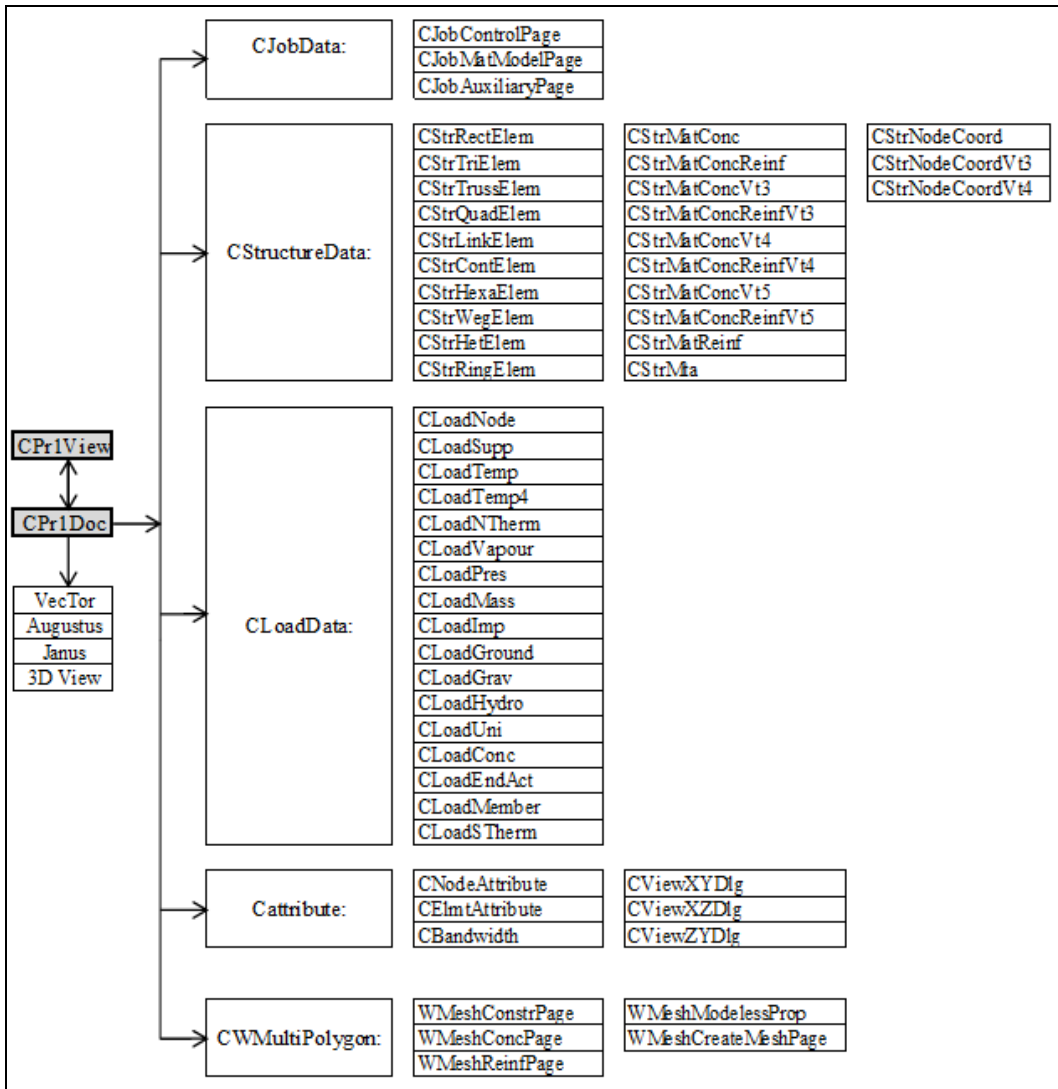


Figure 1: FormWorks source code structure

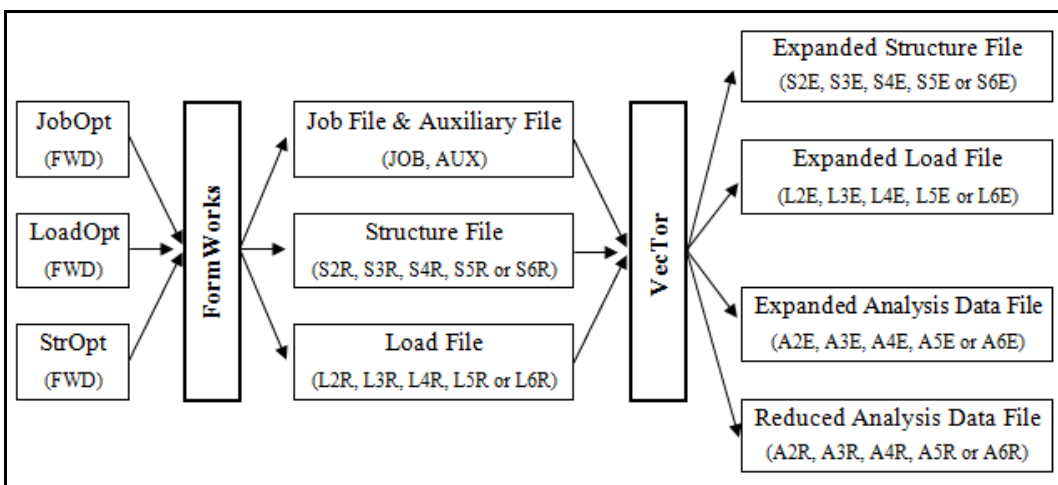


Figure 2: Input and output files for FormWorks and VecTor

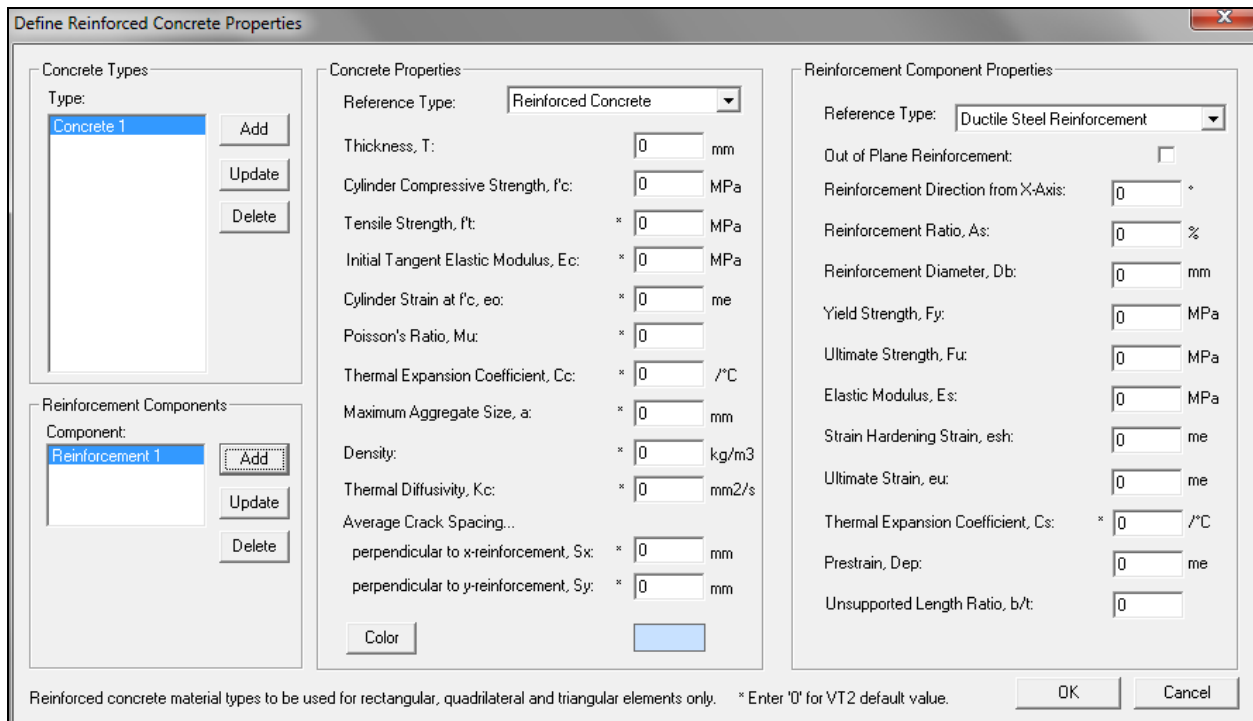


Figure 3: Define Reinforced Concrete Properties window when Reinforced Concrete type is selected as the main material type

Although referred to as Reinforced Concrete, a wide variety of materials can be defined in this section and analyzed in VecTor2. According to the selected Reference type, dialog boxes for material properties will change.

Table 1: Comparison between new and old versions of FormWorks material types

FormWorks Version	Material Types	
	Type	Components
FormWorks 2.0	Reinforced Concrete	Ductile Steel reinforcement
	Reinforcement	---
	Bond	---
FormWorks 3.7 & FormWorks-Plus	Reinforced Concrete	Ductile Steel reinforcement
		Prestressing Steel
		Tension (or Compression) only Reinforcement
		External Bonded FRP Fabric
		Steel-Fibre-Hooked (or Straight)
		Steel Skin Plate
		SFRC Laminate-Hooked (or Straight) Fibre
		Orthotropic Laminate
	Shape Memory Alloy Type 1 (or Type 2)	
	Structural Steel	---
	Masonry	SFRC Laminate-Hooked (or Straight) Fibre
Wood (fixed orthotropic)	---	
Reinforcement	---	
Bond	---	

Table 1 compares material types in recent versions of FormWorks with the previous version of FormWorks. Brief descriptions of the above concrete materials and reinforcement components are included in the following sections.

3.1 Reinforced Concrete

In recent versions of FormWorks and VecTor2 Reinforced Concrete material type includes several new reinforcement components. Following is a short explanation of some of these components.

- **Steel-Fibre-Straight (or Hooked)**

The two types of steel fibres that can be modeled in VecTor2 are straight fibres and hooked fibres. The main difference between the two types of fibres is in the quality of bond between the fibres and the concrete matrix. The deformed ends of the hooked fibres enable a stronger bond between the steel fibres and the concrete compared to straight fibres.

The effect of fibres on the behaviour of concrete is dependent on fibre volume content, fibre length, fibre aspect ratio, fibre tensile strength, concrete strength, and fibre orientation. The majority of these are required inputs in FormWorks.

- **Steel Skin Plate**

Steel-concrete composite wall elements typically consist of a thick concrete core integrated with two thin steel faceplates. Forces are generally transferred between the concrete and the steel mainly by shear studs. In VecTor2, the Distributed Stress Field Model (Vecchio, 2000) is the basis for the analysis of Concrete-Steel Laminates. As VecTor2 is a 2D finite element program, the different materials must be modeled as a smeared/combined element with properties representative of the two materials, as described fully by Vecchio and McQuade (2011). A typical Concrete-Steel Laminate is illustrated in Figure 4(a).

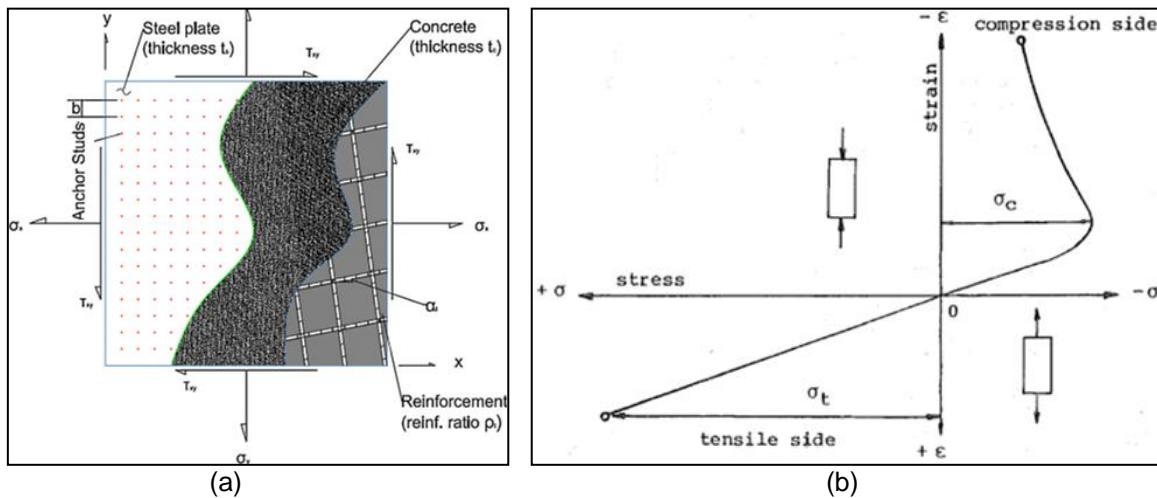


Figure 4: (a) Concrete-Steel Laminate material (Vecchio & McQuade, 2011) (b) The stress-strain curve for wood (Hasebe & Usuki, 1989)

- **Orthotropic Laminate**

The Concrete-Ortho Laminate is a combination of a concrete core and wood (or other orthotropic material) faceplates. Concrete-wood laminates are commonly used in both floor and beam construction. In new floor construction, solid concrete is typically placed on timber floor beams or a solid layer of wood. The wood layer functions to replace the cracked concrete-steel reinforcement section of a solid concrete

slab. Similarly, deep beams benefit from concrete-wood composite construction, as wood can help reduce or eliminate the high tensile stresses in the concrete. Hence, bridges can also utilize composite concrete-timber decks. As with other laminates, forces must be transferred between the concrete and the wood, most likely through shear studs. For the stress-strain behaviour of orthotropic wood, see Figure 4(b) (Gutkowski, et al., 2010).

- **SFRC Laminate—Hooked (or Straight) Fibre**

Similar to the Concrete-Steel Laminate, a Concrete-SFRC Laminate combines a concrete core with steel-fibre reinforced concrete surface layers. Using an SFRC laminate will result in a higher capacity and a more ductile response. A common application of the SFRC laminate is in strengthening of RC walls or slabs, whereby a thin layer of SFRC is attached to an existing RC surface. There are also benefits in shear capacity. An overlay of SFRC allows for increased post-cracking residual stress as the steel fibres are efficient at controlling large cracks in most circumstances (Bonaldo, Barros, & Lourenco, 2005).

In the Reference Type drop-menu, the user can also select Masonry instead of Reinforced Concrete to model Masonry-SFRC laminate.

- **Shape Memory Alloy Type 1 and Type 2**

Shape Memory Alloy (SMA) materials can be used to replace conventional reinforcing steel in seismic situations, useful due to the material’s ability to dissipate large amounts of energy without excessive permanent deformation. The hysteresis for conventional reinforcing steel includes large strain offsets; after an earthquake, the structure may be left with a large residual displacement. Shape memory alloys minimize or eliminate these large strain offsets such that after a seismic event, the structure will retain its original shape or the deformations will be much smaller than if conventional reinforcing steel was used.

The idealized behaviour of SMA, with no strain offsets is modeled with Shape Memory Alloy 1. Shape Memory Alloy 1 has a flag-shaped hysteresis, as shown in Figure 5. Developed at the University of Ottawa, the hysteresis for Shape Memory Alloy 2 differs from SMA 1 in that it incorporates strain hardening as well as small strain offsets. In FormWorks, the input parameters are the same as for Ductile Steel Reinforcement.

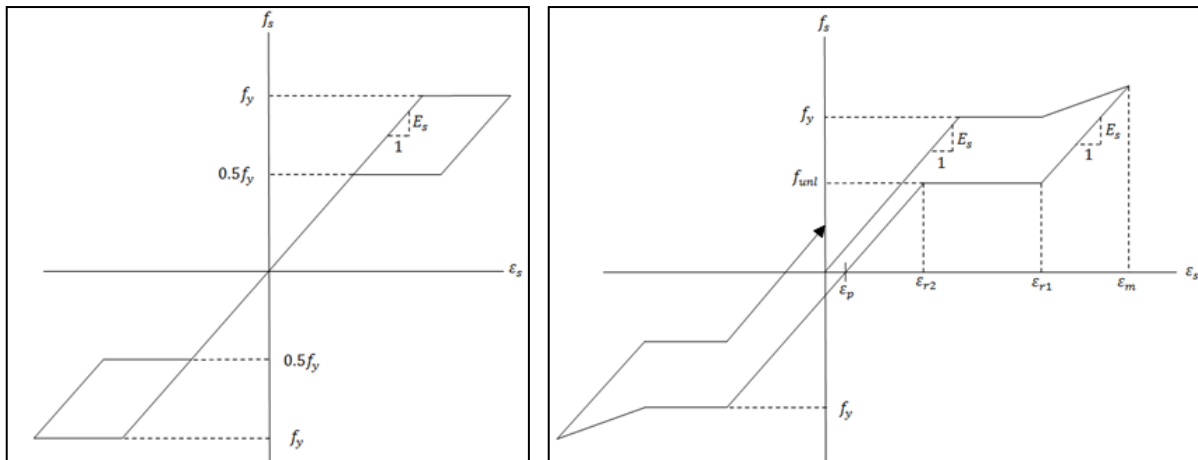


Figure 5: The stress-strain response for Shape Memory Alloy 1 (left) and Shape Memory Alloy 2 (right)

3.2 Structural Steel

Structural Steel is modeled in VecTor2 as a linear-elastic material up to the point of yielding, after which plastic deformation and strain hardening occur. For the most part, the input parameters for Structural Steel in FormWorks are similar to those for Ductile Reinforcement Steel.

3.3 Masonry

Masonry is a composite material consisting of concrete or clay brick units and mortar joints. Masonry is an orthotropic material, due to the geometry and different mechanical properties of the units and joints, as shown in Figure 6. As with the smeared crack approach to the analysis of cracked concrete, for sufficiently large masonry structures, the masonry can be modeled as a continuum with average properties where joint failures are smeared across the single finite element (Lourenco, 1996).

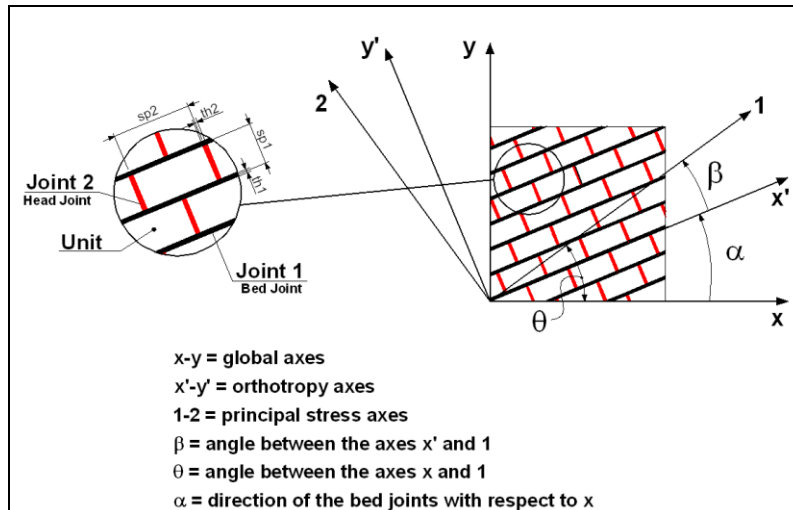


Figure 6: The principal directions wrt x-axis for Masonry Structures (Schlöglimann, 2004)

3.4 Wood (fixed orthotropic)

In VecTor2, wood is modeled as a fixed orthotropic material. The two directions of orthotropy are parallel to the grain and perpendicular to the grain. The longitudinal direction is defined as parallel to the grain; the transverse direction is perpendicular to the grain. When modeling wood in FormWorks, the user must define the properties in both the longitudinal and transverse directions. The stress-strain curve for wood is shown in Figure 4(b) (Hasebe & Usuki, 1987).

For full description of material types and instruction on input parameters refer to Sadeghian (2012).

4 FormWorks-Plus Features

FormWorks-Plus is the newest version of FormWorks, compatible with entire suite of VecTor programs. Following is a brief description of FormWorks-Plus features.

4.1 Load, Element and Material Types

After starting the program, a window automatically pops up requiring the user to specify the type of structure that is going to be modeled. By selecting the type of structure, FormWorks-Plus activates the related VecTor program. This implies that all the material types, loads, node types and element types which are related to that VecTor program will be activated. To make FormWorks-Plus compatible with entire suite of VecTor programs, four different types of node coordinate definitions, five types of elements, several types of load, and various new material properties were added to the software. The following tables compare the Load, Element and Material types of FormWorks-Plus with previous version of FormWorks.

Table 2: Comparison between FormWorks 2.0 and FormWorks-Plus element types























FormWorks Version	VecTor Type	Element Types
FormWorks 2.0	VT2:	      Rectangular Triangular Quadrelateral Truss Link Interface
FormWorks-Plus	VT2:	      Rectangular Triangular Quadrelateral Truss Link Interface
	VT3:	   Hexahedral Wedge Truss
	VT4:	  9 Noded Shell Truss
	VT5:	 Frame Element
	VT6:	    4-Node Axisymmetric 3-Node Axisymmetric Truss Ring bars

Table 3: Comparison between FormWorks 2.0 and FormWorks-Plus load and material types

Version	Type	Load and Material Types
FW 2.0	VT2:	2D Nodal loads: Joint Loads; Support Displacements; Lumped Mass; Impulse Forces 2DElement Loads: Gravity Loads; Element Temperature; Concrete Prestrain; Ground Acceleration Material Types: Reinforced Concrete; Reinforcement; Bond
FW-Plus	VT2:	2D Nodal loads: Joint Loads; Support Displacements; Nodal Temperature; Lumped Mass; Impulse Forces 2DElement Loads: Gravity Loads; Element Temperature; Concrete Prestrain; Ground Acceleration Material Types: Reinforced Concrete; Structural Steel; Masonry; Wood; Reinforcement; Bond;
	VT3:	3D Nodal loads: Joint Loads; Support Displacements; Nodal Temperature; Lumped Mass; Impulse Forces; Vapour Pressure 3DElement Loads: Gravity Loads; Element Temperature; Concrete Prestrain; Ground Acceleration Material Types: Reinforced Concrete; Structural Steel; Masonry; Wood; Reinforcement; Bond;
	VT4:	3D Nodal loads: Joint Loads; Support Displacements; Lumped Mass; Impulse Forces 3DElement Loads: Gravity Loads; Element Temperature; Concrete Prestrain; Ground Acceleration; Hydrostatic Loads; Uniform Loads Material Types: Reinforced Concrete; Reinforcement
	VT5:	2D Nodal loads: Joint Loads; Support Displacements; Lumped Mass; Impulse Forces 2DElement Loads: Gravity Loads; Element Temperature; Concrete Prestrain; Ground Acceleration; End Action Loads; Concentrated Loads; Uniform loads Material Types: Reinforced Concrete
	VT6:	2D Nodal loads: Joint Loads; Support Displacements; Nodal Temperature; Impulse Forces 2DElement Loads: Gravity Loads; Element Temperature; Concrete Prestrain; Ground Acceleration Material Types: Reinforced Concrete; Reinforcement

4.2 View Toolbar

- **XY, XZ and ZY Views** 

This facility allows the user to view the finite element model from different planes. For each plane, there are two viewing options one can select. The first is a sectional view which enables making a section in a specified coordinate. The second option is to view the projection of the structure on different planes. This can be helpful when the user wants to view the change in material types or loads in entire finite element model. For each Viewing dialog box there are two projection views. One displays the projection of the structure to the right (top) side and the other shows the projection to the left (bottom) side. At the bottom of the main window, the status bar shows the active plane and the location of the section.

- **Quick Section** 

With complex finite element models, finding the exact coordinates of the nodes and making a section at those points can be difficult and time consuming. This feature helps the user to automatically find the next (or previous) node and make a section at that location.

- **3D View** 

Since the graphical tools of the MFC library cannot handle 3D shapes very well, FormWorks-Plus uses a supportive program named “3D View” which, in turn, uses OpenGL (an advance graphical tool) to display complex 3D models.

The following figures show different viewing options for a cylinder structure in FormWorks-Plus:

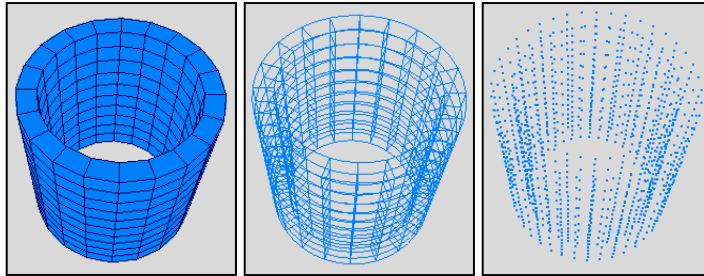


Figure 7: 3D Views in FormWorks-Plus: (a) solid view, (b) mesh view and (c) nodal view

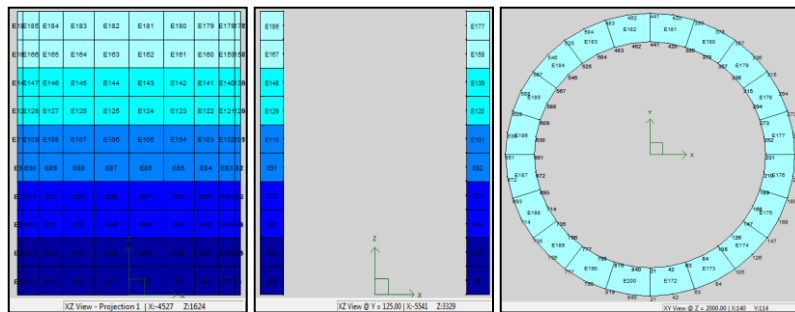


Figure 8: Section and projection views in FormWorks-Plus

4.3 Other Features

There are several other features that have been added to the FormWorks-Plus to make it more powerful pre-processor. For example, a polar coordinate system has been included, greatly facilitating the modelling process of curved structures. A window selection beside pointer selection makes the process of selecting nodes, elements, restraints and loads easier for the user. In the load file, a summary page for

the Ground Acceleration Load and a graph feature for the Impulse Forces give the user a better understanding of the applied loads.

For full description of FormWorks-Plus features refer to Sadeghian (2012).

5 Summary and Future Work

The first objective of this study was to develop an updated version of FormWorks, FormWorks 3.7, which is easier to use and compatible with newer versions of VecTor2. The second objective was to create an expanded version of FormWorks, FormWorks-Plus, capable of modeling different types of structures including 2D Membrane Structures, 3D Solid Structures, Shell Structures, Plane Frame Structures, and Axisymmetric Solid Structures. These objectives have been accomplished. The FormWorks programs, and VecTor analysis software, are available for free download.

The current suite of VecTor analysis programs are developed such that each program is applicable to one particular type of structure only; for example, VecTor2 can only model 2D planar continuums and VecTor5 can only model 2D plane frames. There are many applications encountered where several types of structural components act together; for example, in a typical building, a moment resisting frame (2D frame) may act compositely with floor slabs (3D plate) and shear walls (2D continuum). Work is required to develop an integrated analysis program whereby mixed-type structures can be analyzed using the VecTor modeling facilities.

A master program (Cyrus) is currently under development which will serve to define principal nodes that are shared between two or more sub-elements of the structure; the computed displacement at each of these master nodes will be enforced in the analyses of the sub-elements performed using the appropriate VecTor programs. The program architecture employed will allow the use of parallel processing, resulting in quicker and more efficient simulations.

The final goal is to produce a software package including a preprocessor (FormWorks-Plus), a post-processor (Janus) a main program (VecTor) and a coordinator(Cyrus) which allows the user to model single-type or mixed-type structures, analyze each substructure using appropriate VecTor program while including the interaction effects by Cyrus coordinator, and finally display the analysis results.

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