DEVELOPMENT OF A COLLABORATIVE DESIGN TOOL FOR STRUCTURAL ANALYSIS IN AN IMMERSIVE VIRTUAL ENVIRONMENT

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ABSTRACT

This paper contains the results of an on-going collaborative research effort by the departments of Architecture and Computer Science of Virginia Polytechnic Institute and State University, U.S.A., to develop a computer visualization application for the structural analysis of building structures. The VIRTUAL-SAP computer program is being developed by linking PC-SAP4 (Structural Analysis Program), and virtual environment software developed using the SVE (Simple Virtual Environment) library. VIRTUAL-SAP is intended for use as a collaborative design tool to facilitate the interaction between the architect, engineer, and contractor by providing an environment that they can walk-through and observe the consequences of design alterations. Therefore, this software can be used as an interactive computer-aided analysis of building systems.

INTRODUCTION

During the last decade there have been significant advances in the areas of computer visualization and graphics. The development of technologies such as the CAVE [Cave Automated Virtual Environment] (Cruz-Neira et al, 1993) has provided a unique opportunity to allow a user to immerse himself/herself in a virtual world that presents a realistic view of a building model. Moreover, through the use of three-dimensional input devices and interaction techniques (Bowman et al. 2001), the user can create or modify a model while immersed within it.

Even though there is a large body of research on the subject of virtual environments (VEs), there have only been a few attempts to use this new tool for real-world scientific purposes. Among them the following are notable:

Impelluso (1995) presented one of the first attempts to create a "Physically-Based Virtual Reality". By linking a linear three-dimensional finite element program with a visualization application, he could present the small deformations of virtual objects subjected to various loading conditions. This effort has later been extended to include the non-linear behavior of objects (Impelluso 1998).

Yeh, and Vance (1995) used virtual-reality techniques to provide a computer-generated environment for the designer to investigate design changes by manipulating virtual objects. They used this approach to perform an interactive sensitivity analysis and design optimization of a cantilever beam in virtual environment.

Murakami, et al. (1998) developed a Virtual Reality (VR) based computer aided design system for Tensegrity Structures. The VR-based CAD system allows the user to interact with virtual structures through joysticks which apply reaction forces computed by the finite element code.

A prototype of performing real-time simulation of mechanical systems in immersive virtual environments has been developed to run in the CAVE and on the ImmersaDesk at the Argonne National Laboratory (Canfield 1998). The system can display three-dimensional objects in the CAVE and project various scalar fields on to the exterior surface of the objects during real-time executions. Finite element software has been linked to VR for mainly thermal stress analysis of complex mechanical systems.

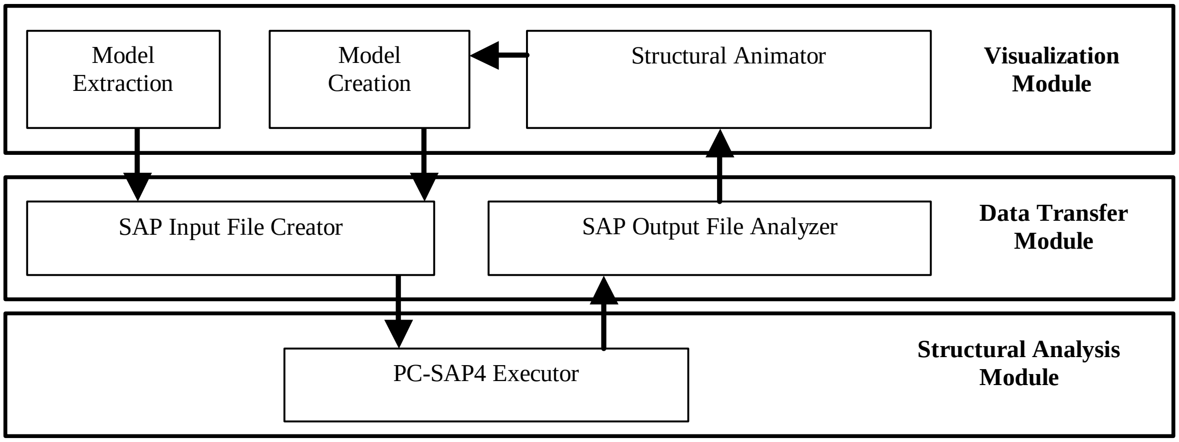


Fig. 1: VIRTUAL-SAP Software architecture

In the area of architectural/structural engineering, there is not any available software that can have both the high quality graphical interfaces and computational capabilities. Using computer packages such as AUTOCAD (AutoDesk, Inc. 2000) and 3D STUDIO MAX (AutoDesk, Inc. 2000), etc., architects can create detailed images with high resolution graphics, however, these programs lack any computational capability to predict the behavior of buildings under different environmental conditions. On the other hand, structural engineering programs such as SAP-2000 (Computers and Structures, Inc. 2000), STAAD-Pro2001 (Research Engineers International 2000), RISA (Risa Technologies, Inc. 2000), etc., are being used by engineers to analyze building structures under different loading conditions. Even though these programs have graphical user interfaces, they are not user-friendly, do not have high quality graphics, and are not suitable for use by non-technical individuals.

This paper describes different stages of the development of VIRTUAL-SAP, which is part of an on-going project at Virginia Tech. The main objective of the first phase of this project, which will be discussed here, is to create a software package to close the gap between the two classes of available programs as mentioned above such that the user will be immersed in the virtual environment and can interact with the building model. In addition, this software can be used by the design team to check the consequences of different design strategies. The future phase of this project involves the use of VIRTUAL-SAP to study the interaction of structural and non-structural building elements during low to moderate level seismic activities.

DEVELOPMENT OF VIRTUAL-SAP

Using the VIRTUAL-SAP software package, a computer model of a structure can be constructed in a VE. This model is a three-dimensional representation of the building system. The virtual model will eventually be able to include the structural system, the architectural, and non-structural components of building such as cladding, partitions, ceiling systems, and mechanical systems.

Once a model is created, the structural data of that model is sent to the PC-SAP4 program in the form of a SAP input file. The PC-SAP4 program processes the data and generates the instantaneous structural information of the model in the form of SAP output file. Based on this information, the VIRTUAL-SAP program animates the model to show the effect of the applied loads.

The VIRTUAL-SAP program contains six different software components as shown in Figure 1. Each software component has a distinctive functionality. All six of these software components can further be classified into three modules, described below:

1. Visualization

This module consists of “C” language code that uses the SVE library (Kessler et al, 2000). It presents the current building model to the user using three-dimensional computer graphics. The model is rendered from the current viewpoint, which the user can control interactively. The module also allows the user to select different building elements, define their geometric and material properties, assemble the building, and subject it to different loading conditions.

There are two different kinds of user interfaces for the visualization module. The first interface presents the 3D graphics in a window on the user's desktop, and is controlled via a standard mouse and keyboard. This allows for quick verification of a model or simulation of the results, and allows members of the design team to view the structure at the same time.

However, in order to get a better sense of the scale, shape, and movement of the model, the second interface uses a head-mounted display (HMD), tracking system, and two three-dimensional input devices (a stylus and tablet) to create an immersive VE. The HMD blocks the physical world so that the user only sees the virtual world. The tracking system is used to track the user's head motions, and thus to allow a natural way to control the viewpoint (by turning the head). The input devices are used to build or modify the model, to start the simulation, to fly to a different area of the virtual world, etc.

It is quite difficult to achieve the same precision of input in a three-dimensional VE as one has with a standard desktop computer. Therefore, a two-dimensional interface is placed within the three-dimensional virtual world, using the "pen and tablet" interaction technique (Angus and Sowizral, 1995). In this technique, the user holds a physical stylus and tablet (Figure 2a), and sees a virtual stylus and tablet in the VE (Figure 2b). By placing interface elements like buttons or menus on the virtual tablet, a virtual 2D interface with a physical constraint is created. The tablet is used for the creation of structural components, the presentation of an overview map of the space, and to start the simulation and resulting animation of the model.

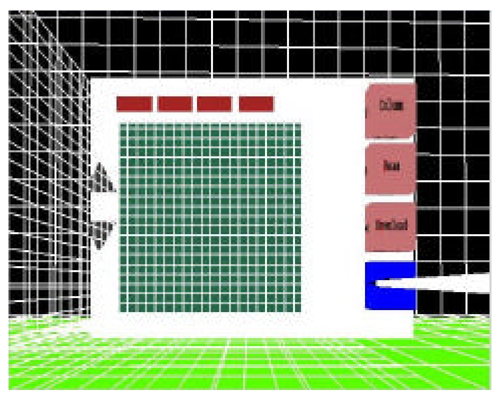
This interface also allows the direct manipulation of structural elements in three dimensions. The virtual pen can be used to select objects by touching them, and then to drag the objects to new locations in the virtual world. Objects are snapped to a three-dimensional grid to allow precise placement. Finally, the user can "fly" around the virtual world by pointing the pen in the desired direction of movement and holding down a button. This allows the user to obtain any point of view, both inside and outside the building model. The software components 'Model Creation' and 'Model Extraction' both fall in this category. 'Model Creation' refers to creating a structure from scratch in the 3D environment and 'Model Extraction' refers to importing the structure of the model from a SAP input file.

The "Structural Animator" component also falls within this module category. This component is responsible for showing how the structure behaves subjected to a dynamic loading condition.

2. Structural Analysis Module

This module consists of a widely used structural software for the analysis of building structures. The program that is used here is PC-SAP4, originally developed at the Department of Civil Engineering of the University of California, Berkeley (Maison 1994).

(a)



(b)

Fig. 2:
(a) Physical devices used in the pen and tablet interaction technique;
(b) Virtual Pen and Virtual Tablet

This software is a finite element program developed for the general analysis of structural systems. Even though it is only limited to linear elastic systems, the ease of use, inclusion of various elements, and the fact that it is an open-source code, have made this program suitable for this study. This software has been modified to accept the data from other modules of VIRTUAL-SAP.

The software component "PC-SAP4 Executor" is responsible for executing this program. The component executes PC-SAP4 as a new child process in the operating system. PC-SAP4 reads the SAP input file and generates a SAP output file when the execution is complete. Upon the completion of execution, "PC-SAP4 Executor" alerts VIRTUAL-SAP, which then reads the SAP output file for all the instantaneous structural information that is present in that file.

3. Data Transfer Module

This module is responsible for the transfer of the structural data and the instantaneous structural information between the VIRTUAL-SAP and the PC-SAP4 program and vice versa. Both the "SAP Input File Creator" and the "SAP Output File Analyzer" components are included in this module.

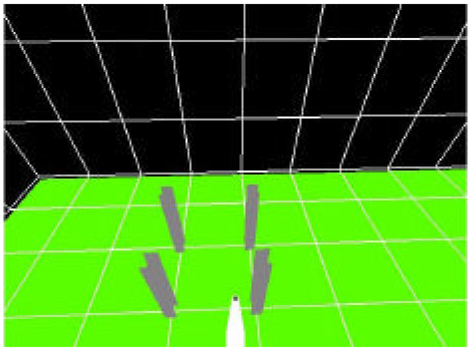
The results of the analysis in the form of the deformed building shape are examined by the "SAP Output File Analyzer" and then are sent back to the Visualization Module to display the building state under the applied forces. The Visualization module uses the software component "Structural Animator" to show the behavior of the model subjected to the varying loads.

Using a menu of building components, the user can modify a computer model within the Visualization Module. A finite element representation of this model can then be transferred to the PC-SAP4 for analysis and subsequent display.

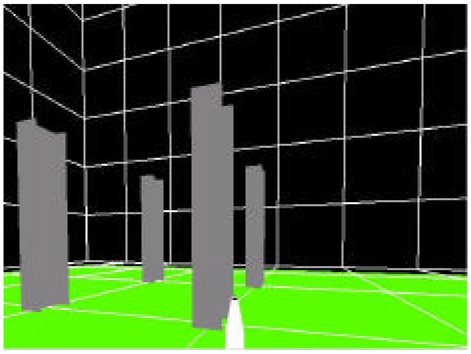
As shown in Figure 1, this cycle can be repeated, which enables the user to observe the consequences of design alterations. This software allows the user to have direct interaction with the model and to walk through the building in the virtual environment.

SIMULATION

Here, different stages of model creation, design alterations, and seismic analysis using VIRTUAL-SAP will be demonstrated. For the sake of clarity, a simple one-story steel structure comprised of four columns and four beams is used. Figure 3 shows different stages of building assembly consisting of erection of columns (Figures 3a and 3b) and the placement of beams (Figure 3c). This building was subsequently subjected to an artificial earthquake excitation along two perpendicular horizontal directions. The building was animated in real-time. Figure 4 shows a few frames of this animation.



(a)



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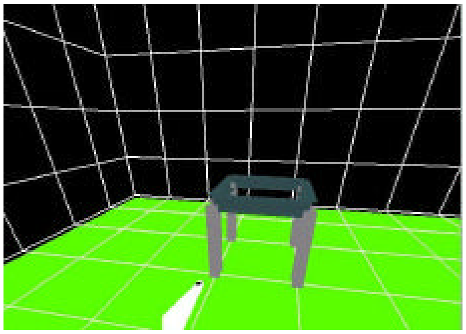


(c)

Fig 3:

(a) Four columns on the ground in a square (column placement);
(b) Four columns on the ground plane (column placement);
(c) View of building including beam placement

APPLICATION

The main applications of VIRTUAL-SAP are for educational and research purposes:

1. Educational Application

Students in building sciences can use VIRTUAL-SAP to learn about the behavior of different structural systems, and building elements subjected to various environmental conditions. They can interact with the building in an immersive virtual environment and learn about proportions, different structural and architectural elements, and consequences of design decisions.

Using a motion platform, they can also sense how it feels to be on different locations of a building when an earthquake or high wind happens or how changing different structural elements can affect the building response to earthquakes and high winds.

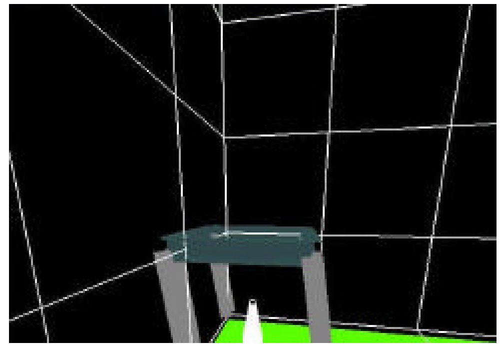
2. Research Application

VIRTUAL-SAP can be used by members of a design team (architect, engineer, contractor) to test and investigate different construction materials, methods of construction, and material handling. In addition, the behavior of architectural components and their interaction with structural elements of the building during extreme loading events such as earthquakes and high winds can be investigated by the engineer and architect.

Architectural components such as partitions, and suspended ceiling systems can be studied. The interaction of these elements with the structural system and each other can be scrutinized. Different conditions for connecting these components to the structure and each other, and requirements such as story drift, relative stiffness of components and their effects on the interaction of the different elements can be studied.

SUMMARY AND CONCLUSIONS

This paper discusses the different stages of development of VIRTUAL-SAP at the Virginia Polytechnic Institute and State University, U.S.A. Different applications of this software were discussed.



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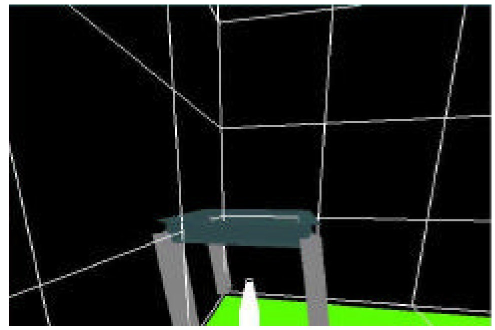

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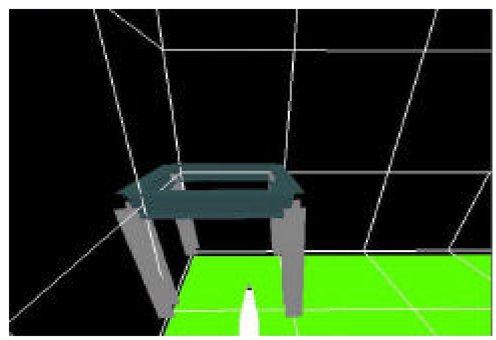

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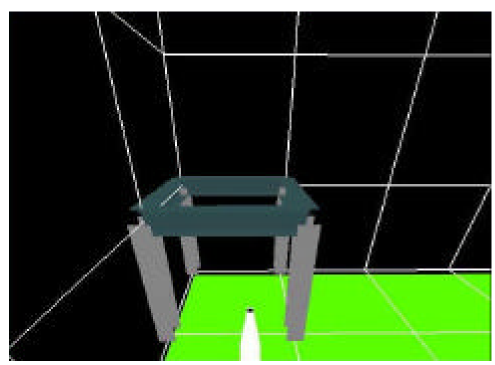

(d)

Fig 4: Building Model Animation

The use of virtual environments as demonstrated in this paper can significantly enhance the understanding of architects, engineers, and contractors of the performance of different building elements during various loading conditions such as earthquakes, winds, etc.

Future developments of VIRTUAL-SAP include additional element types, selection of element materials and properties, and more intelligent placement of virtual objects. In addition, novel user interface strategies for this application will be developed and tested.

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REFERENCES

Angus, I. and Sowizral, H., “Embedding the 2D Interaction Metaphor in a Real 3D Virtual Environment”, Proc. of SPIE, Stereoscopic Displays and Virtual Reality Systems, 1995.

AutoDesk, Inc., “AUTOCAD 2000-Automated Computer Aided Drafting”, San Rafael, California, 2000.

AutoDesk, Inc., “3D Studio Max”, San Rafael, California, 2000.

Bowman, D., Kruijff, E., LaViola, J., and Poupyrev, I. “An Introduction to 3D User Interface Design”, to appear in Presence: Teloperators and Virtual Environments, vol. 10, no. 1, 2001.

Canfield, T.R., "Simulation and Visualization of Mechanical Systems in Immersive Virtual Environments", Proc. of 12th ASCE Engineering Mechanics Conference, La Jolla, California, May 17-20, pp. 182-187, 1998.

Computers and Structures, Inc., “SAP2000-Static and Dynamic Finite Element Analysis of Structures”, Berkeley, California, 2000.

Cruz-Neira, C., Sandin, D., & DeFanti, T., “Surround-Screen Projection-Based Virtual Reality: The Design and Implementation of the CAVE”. Proceedings of ACM SIGGRAPH, 1993.

Impelluso, T.J., "Physically-Based Virtual Reality", GII Testbed and HPC Challenge Applications on the I-WAY, Ed. Korab, H., Brown, M., ACM/IEEE SC'95, 1995.

Impelluso, T.J., "Physically-Based Virtual Reality: Integrating FEM and Visualization", Proc. of the 12th ASCE Engineering Mechanics Conference, La Jolla, California, May 17-20, pp. 178-181, 1998.

Kessler, G., Bowman, D., & Hodges, L., “The Simple Virtual Environment Library: An Extensible Framework for Building VE Applications”, Presence: Teleoperators and Virtual Environments, vol. 9, no. 2, pp. 187-208, 2000.

Maison, B. F., “PC-SAP4. A Computer Program for Linear Structural Analysis”, Earthquake Energy Research Center, University of California, Berkeley, California, August, 1994.

Murakami, H., Nishimura, Y., Impelluso, T.J., and Skelton, R.E., "A Virtual Reality Based CAD System for Tensegrity Structures", Proc. of the 12th ASCE Engineering Mechanics Conference, La Jolla, California, May 17-20, pp. 197-200, 1998.

Research Engineers International, “STAAD Pro2001-Structural Analysis and Design”, Yorba Linda, California, 2000.

Risa Technologies, Inc., “RISA 3D-Rapid Interactive Structural Analysis”, Foothill Ranch, California, 2000.

Yeh, T.P., and Vance, J.M., “Interactive Design of Structural Systems In a Virtual Environment”, 24th Midwestern Mechanic Conference Proceedings, Vol. 18, Iowa State University, Iowa, pp. 185-187, 1995.