Design of a Versatile Engineering Simulation Environment for Coupled Continuous-Discontinuous Simulation

Wei-Tze Chang[1], Ren-Zuo Wang[2], Shang-Hsien Hsieh[3], Chung-Yue Wang[4], and Kuo-Chun Chang[5]

[1] Assistant Researcher, National Center for Research on Earthquake Engineering, No. 200, Sec. 3, Hsinhai Rd., Taipei 10668, Taiwan (R.O.C.); PH: +886-2-6630-0892; e-mail: aries@iaries.net
[2] Associate Researcher, National Center for Research on Earthquake Engineering, No. 200, Sec. 3, Hsinhai Rd., Taipei 10668, Taiwan (R.O.C.); PH: +886-2-6630-0894; e-mail: rzwang@ncree.narl.org.tw
[3] Professor, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei 10617, Taiwan (R.O.C.); PH: +886-2-3366-4313; e-mail: shhsieh@ntu.edu.tw
[4] Professor, National Central University, No. 300, Jhongda Rd., Jhongli City, Taoyuan County 32001, Taiwan (R.O.C.); PH: +886-2-8732-5567 ext. 1107; e-mail: cywang@cc.ncu.edu.tw
[5] Professor, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei 10617, Taiwan (R.O.C.); PH: +886-2-3366-4232; e-mail: ciekuo@ntu.edu.tw

ABSTRACT

To overcome the difficulty of integrating continuous/discontinuous numerical methods to a software and retain its flexibility at the same time, National Center for Research on Earthquake Engineering (NCREE) under National Applied Research Laboratories (NARL) in Taiwan has designed a Versatile Engineering Simulation ENvironment (named VESEN), which is a coupled continuous-discontinuous simulation platform based on Vector Form Intrinsic Finite Element (VFIFE) method and Discrete Element Method (DEM). Object-Oriented Programming (OOP) technology and design patterns in software engineering are used to facilitate VESEN's software usability and extensibility for adapting future requirement changes involving various constitutive laws, contact detection algorithms, geometric shapes of elements, interaction solvers, control points (in VFIFE method), and member sections. This paper presents the software framework of VESEN with a concept of "solver pool" and illustrates an iterative simulation procedure for ensuring the simulation consistency between rigid and deformable elements. Currently VESEN has been successfully prototyped and tested in studying seismic behavior of bridge models with functional bearings. It can be expected that VESEN can address large-scale deformation and collapse of buildings and soil-structure interaction problems in the future.

INTRODUCTION

Coupled continuous-discontinuous simulation can be applied in studying complex engineering problem such as solid-liquid interaction, estimate the impact on structure caused by earthquake, debris flow, and tsunami. National Center for Research on Earthquake Engineering (NCREE) under National Applied Research Laboratories (NARLabs) in Taiwan has integrated two numerical methods, Vector Form Intrinsic Finite Element (VFIFE) method and Discrete Element Method (DEM), to design a Versatile Engineering Simulation ENvironment (named VESEN, a Norwegian word in a spiritual way means “being”), for the purpose of modelling multi-hazard phenomenon.

Vector Form Intrinsic Finite Element (VFIFE) method. VFIFE is a novel numerical method proposed by Ting (Shih, *et al.* 2004; Ting, *et al.* 2004a and 2004b). Different from traditional Finite Element Analysis (FEA), it is based on Newmark-β method to discretize a structure into control points instead of elements for solving governing equations. The continuity constraints are not enforced in VFIFE which makes it capable of simulating large-scale motion, deformation, even failure behavior of structure (Wang 2005). Besides, vector-form motion equations in VFIFE also ease implementation tasks in programming (compared to the matrix-form structure analysis approach). Currently VFIFE has been successfully applied to study structure failure and collapse (Wang, *et al.* 2006), structure fire response (Lien 2009), and offshore template platform (Chang, *et al.* 2010).

Discrete Element Method (DEM). DEM was first proposed by Cundall (1971) and its more general form was given by Williams, *et al.* (1985). DEM focuses on modelling granular and discontinuous material. Currently it has been widely used in various fields such as civil engineering (Chang 2009), agriculture (Ribas, *et al.* 2010), and granular flow (Yang, *et al.* 2013). Also, DEM has been combined with FEA and Computational Fluid Dynamics (CFD) methods (Chang, *et al.* 2011; Munjiza 2004) for modelling continuum-discontinuum system and is introduced into VESEN to provide the ability in dealing with complex interactions between solid interfaces.

DESIGN OF VESEN

VESEN Framework. After analyzing the requirement of concepts from VFIFE’s research, this study lists eight major types of concepts for designing VESEN framework: (1) constitutive law between stress/strain or force/displacement, (2) contact detection algorithm, (3) element, (4) failure criterion, (5) geometric shape for illustrating boundary of element, (6) points, (7) interaction solvers, and (8) cross section of structure member. This study modifies and extends the VErsatile Discrete Objects (VEDO) framework (Yang and Hsieh 2005; Chang and Hsieh 2009) to develop VESEN’s object-oriented framework (see Figure 1) that includes all of the above concepts in classes. Inherited from the VEDO framework, VESEN also focuses on the interaction between elements. For fulfilling the physical meaning of a coupled continuous-discontinuous simulation environment, the names of some classes from the VEDO framework were changed, as shown in Table 1. The details of VESEN framework involve: (1) how to decouple data and solver in numerical models, (2) design of "solver pool" for import new models, (3) procedure for coupling deformable and rigid elements in simulation, (4) design of "composite object" for detecting contact between elements with complex geometric shapes, and (5) design of "composite cross section" for user-defined structure members. Due to length limitation of the present paper, only the first three items are discussed further below.

Table 1. Class table of VEDO and VESEN (abstract classes are in *italics*).

Issue	Class of VEDO	Class of VESEN
Interaction between elements	Interaction	Interaction
	ImpactSolver	*InteractionSolver*
	ContactDetecor	Contact & *ContactSolver*
	DiscreteObject	*VESENOvject* & its subclasses
Data structure & simulation procedure control	DOWorld	VESENWorld
	Consultant	*Consultant*
	SimMediator	SimMediator
	DOContainer	ElementContainer, PointContainer, & InteractionContainer

Decoupling of data and solver in numerical models. An object with physical meaning in VESEN is divided into two parts, data (classes with symbol "#") and solver (classes in gray). This design uses the "bridge pattern" in software engineering (Gamma, *et al.*, 1995) to decouple the data from the implementation of solution methods and reduce the complexity of adding new models (see Table 2).

Table 2. The classes in VESEN using the design of "bridge pattern".

Physical meaning	Data class	Solver class
Constitutive law	ConstitutiveLaw	*ConstitutiveLawSolver*
Contact detection algorithm	Contact	*ContactSolver*
Element	Element	*ElementSolver*
Failure criterion	FailureCriterion	*FailureSolver*
Geometric shape	GeometricShape	*GeometricShapeSolver*
Point	Point	*PointSolver*
Interaction	Interaction	*InteractionSolver*
Section	Section	*SectionSolver*

Solver pool. To make things easier for model designers in adding and testing their new models without touching the core of VESEN, we design a "solver pool" (i.e. the "SolverPool" class) for managing these models. In the beginning, the main program imports all solvers into the "solver pool" as candidates for simulation. The name of a solver (reported by the class itself) is the index for searching the solver in the pool (see Figure 2a). After that, VESEN gets the parameters (data) and the name of solver from the input file (see Figure 2b). At this step, the relationship between element and the designated element solver is built. With the help of "bridge pattern" as mentioned above, the function of "*ElementSolver*" is independent of the data in "Element" (see Figure 2c). Only two lines of codes have to be added in main function and the other existing codes will not be touched when importing a new solver into VESEN (bold words in Figure 2a). Not only for the convenience for the designer of new model, but also the knowhow of individual models can be protected with this design.

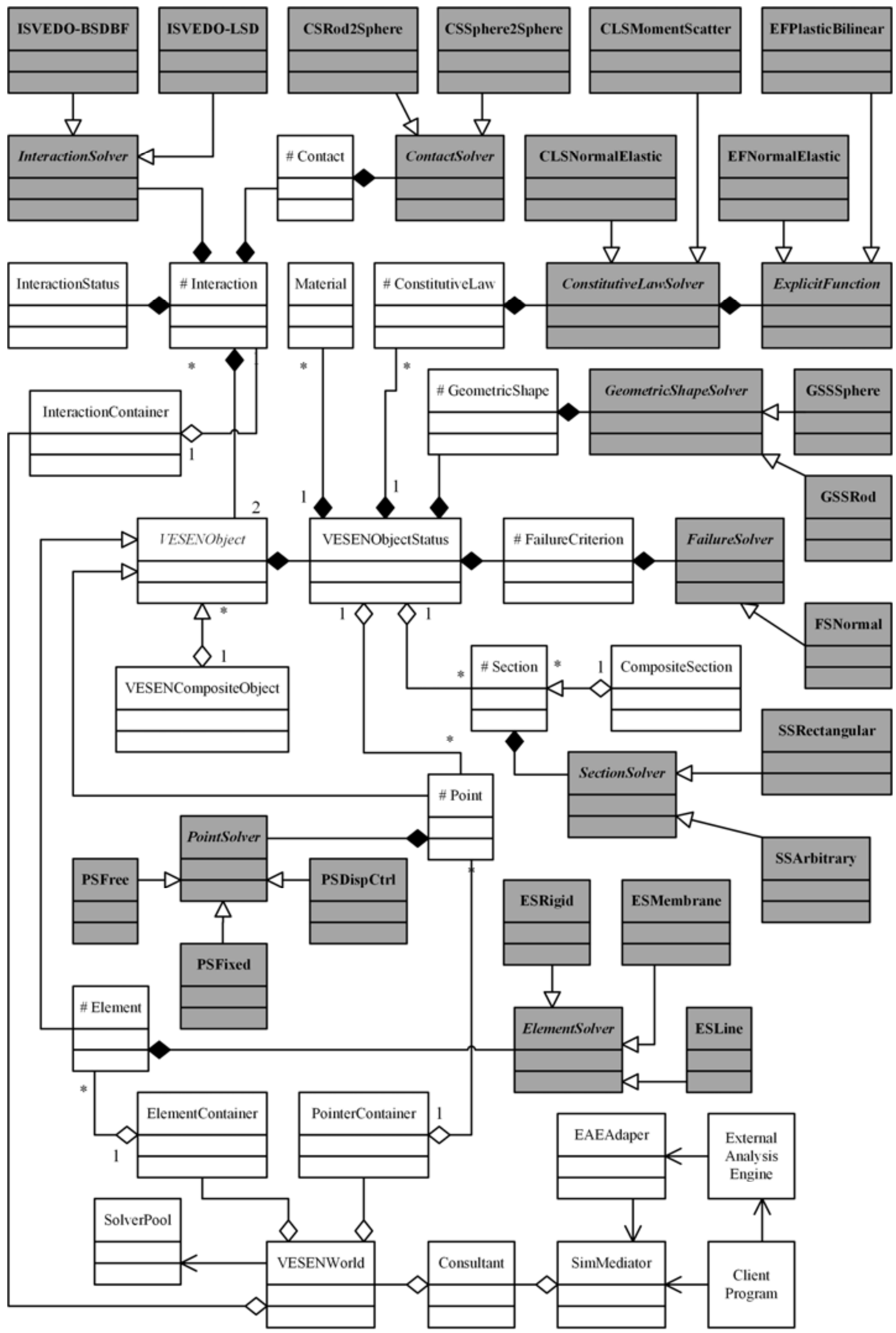
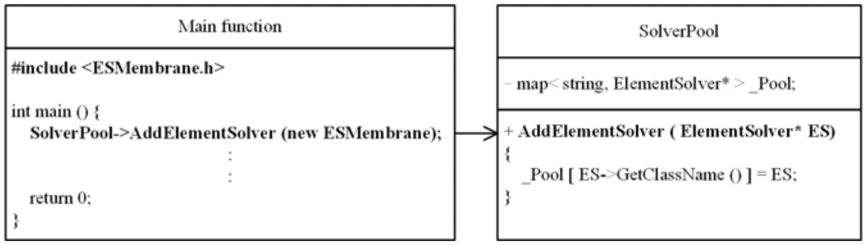
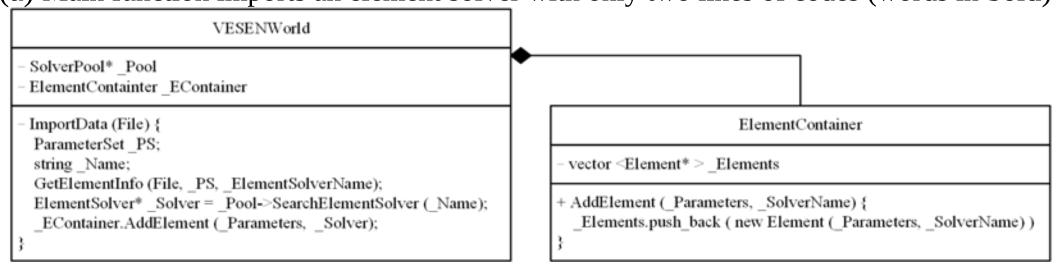


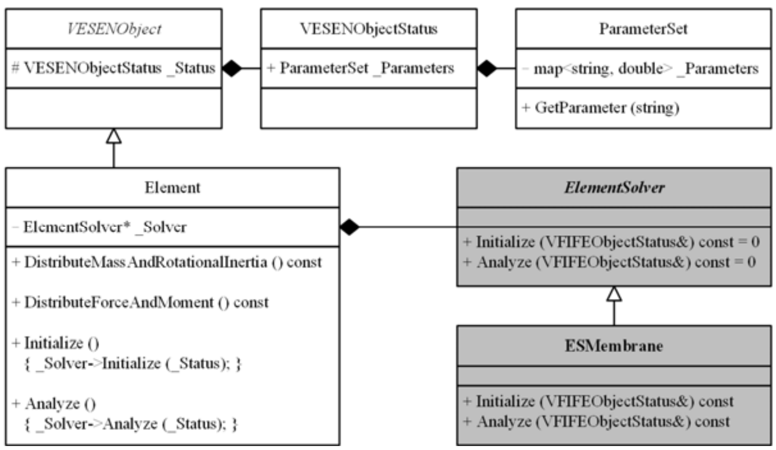
Figure 1. VESEN framework in class diagram. Name of class in italics indicates abstract classes. Names with symbol "#" and in gray color indicate "data" and "solver", respectively.



(a) Main function imports an element solver with only two lines of codes (words in **bold**)



(b) "VESENWorld" gets parameters and the name of element solver from the input file



(c) Design of "Element" and "*ElementSolver*" classes using "bridge pattern"

Figure 2. It is easy to add a new element solver in VESEN with the design of solver pool.

Procedure for coupling simulation with deformable and rigid elements. VESEN has to deal with the coupling of deformable and rigid elements the whole time. In the VFIFE method, rigid blocks are treated as deformable objects with high stiffness which leads to tiny time steps and considerable computation. In contrast, DEM ignores deformation of all elements and allows "overlap" to estimate an equivalent contact force in exchange for higher computing efficiency. To keep both advantages, this study designs a coupling simulation procedure for integrating deformable and rigid elements (see Figure 3). Control points are classified into three types: control points in deformable elements (VFIFE element), control points in rigid element (DEM element),

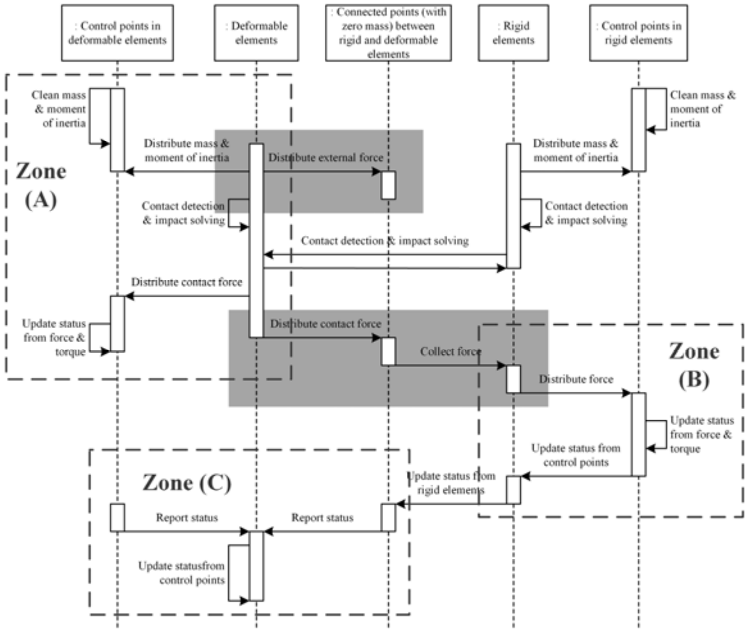


Figure 3. Sequential diagram for coupling simulation with deformable and rigid elements in VESEN and connected points. When deformable elements finish the procedure related to their control points (zone A), external and contact forces are transmitted to rigid elements (gray part) and the states of the rigid elements are updated (zone B). After that, the states of the deformable elements are again updated from the control and connected points.

CONCLUSION - CURRENT STATE OF VESEN AND FUTURE WORK

Currently the prototype of VESEN has been developed with 25 numerical models in 8 types (see Table 3) and used to study large-scale deformation of a truss system (see Figure 4). Once necessary implementation for modelling building structure (such as VFIFE frame elements) is completed, VESEN will be used to study seismic performance of bridges with functional bearing systems and collapse behavior of structures. The simulated results will be verified using experimental data obtained at NCREE.

Table 3. Models in the prototype of VESEN

Physical meaning	Model
● Constitutive law	Elastic linear model, elastic bilinear model, table-based model, and ASCE soil spring model
● Contact detection algorithm	Algorithm for sphere-to-sphere, sphere-to-rectangular-plate, and sphere-to-cylinder
● Element	Truss element, frame element, 4-points rigid element, and 8-points rigid element
● Failure criterion	Maximum allowable tensile/compressive failure
● Geometric shape	Sphere, ellipsoid, rectangular plate, and cylinder
● Point	Time-control-displacement point, fixed point, 6-DOFs point, hinge point, and sliding hinge point
● Interaction solver	Linear-spring-dashpot model, Hertzian contact model, and 7-parameters-DEM model
● Cross section	Rectangular section, circular section, and user-defined section

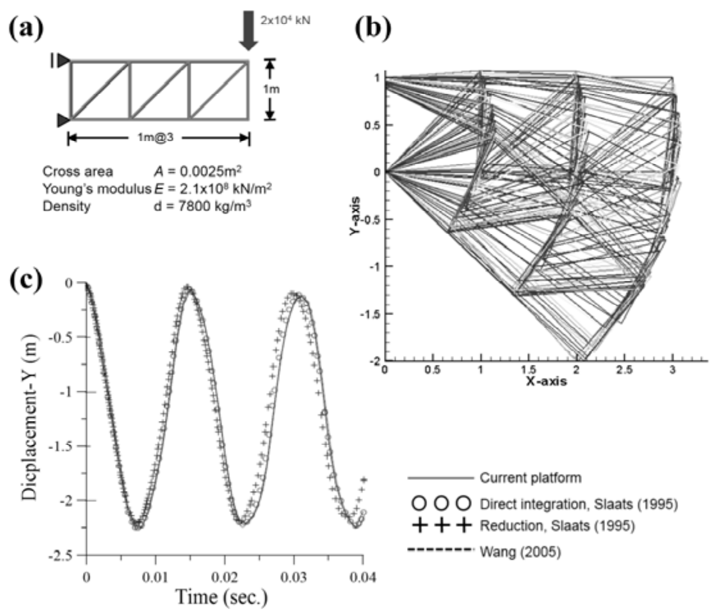


Figure 4. Application of VESEN to studying large-scale deformation of a truss system (Slatts, *et al.*, 1995): (a) setup; (b) dynamic response; (c) comparison of results of the displacement at bottom-right point.

REFERENCES

Chang, W. T. (2009). "Parallel Discrete Element Simulation and Its Application to the Study of Solid-liquid Flow Behavior," Ph.D. Dissertation, National Taiwan University, Taipei, 124 pages.

Chang, W. T., and Hsieh, S. H. (2009). "Parallelization of Discrete Element Simulation," *Journal of the Chinese Institute of Engineers*, 32(6), 825-841.

Chang, W. T., Hsieh, S. H., Yang, F. L., Chen, C. S., and Lin, S. R. (2011) "Extension of VEDO System for CFD-DES Hybrid Simulation," *Proceedings of the 3rd International Symposium on Computational Mechanics and 2nd Symposium on Computational Structural Engineering*, December 5-7, Taipei, Taiwan 2011.

Cundall, P. A. (1971). “A Computer Model for Simulating Progressive, Large Scale Movement in Blocky Rock System,” *Proceeding of ISRM Symposium on Rock Fracture*, Nancy, France, 129-136.

Chang, P. Y., Lee, H. H., Tseng, G. W., and Chung, P. Y. (2010). “VFIFE Method Applied for Offshore Template Structures Upgraded with Damper System,” *Journal of Marine Science and Technology*, 18(4), 473-483.

Gamma, E., Helm, R., Johnson, R., and Vlissides, J. M. (1995). *Design Patterns: Elements of Reusable Object-Oriented Software*, Addison-Wesley Longman, Boston, USA, 416 pages.

Lien, K. H. (2009). “Vector Form Intrinsic Finite Element Analysis of Steel Structures Exposed to Fire,” Ph.D. Dissertation, National Cheng Kung University, 191 pages (in Chinese).

Munjiza, A. (2004). *The Combined Finite-Discrete Element Method*, Wiley, 352 pages.

Ribas, R. M. G., Ribas, V. R., Martins, H. A. L., Ribas, V. R., Carneiro, S. M. O., Albuquerque, R. N., and Andrade, P. H. S. (2010). “Stress Effects on Food Handler Attention in A Public Hospital in Recife-PE, Brazi,” *Dement Neuropsychol*, 4(4), 325-331.

Shih, C., Wang, Y. K., and Ting, E. C. (2004). “Fundamentals of A Vector Form Intrinsic Finite Element: Part III. Convected Material Frame and Examples,” *Journal of Mechanics* 20(2), 133-143.

Slatts, P. M. A., Jongh, J. de., and Sauren, A. A. H. J. (1995) “Model Reduction Tools for Nonlinear Structural Dynamics,” *Computer and Structures*, 54(6), 1155-1171.

Ting, E. C., Shih, C., and Wang, Y. K. (2004a). “Fundamentals of A Vector Form Intrinsic Finite Element: Part I. Basic Procedure and A Plane Frame Element,” *Journal of Mechanics* 20(2), 113-122.

Ting, E. C., Shih, C., and Wang, Y. K. (2004b). “Fundamentals of a Vector Form Intrinsic Finite Element: Part II. Plane Solid Elements,” *Journal of Mechanics* 20(2), 123-132.

Wang, C. Y., Wang, R. Z., and Tsai, K. C. (2006). “Numerical Simulation of the Progressive Failure and Collapse of Structure Under Seismic and Impact Loading,” *Proceeding of 4th International Conference on Earthquake Engineering*, October 12-13, Taipei, Taiwan, Paper No. 84.

Wang, R. Z. (2005). “Vector Form Motion Anylysis of Structure,” Ph.D. Dissertation, National Central University 294 pages (in Chinese).

Williams, J. R., Hocking, G., and Mustoe, G. G. W. (1985) “The Theoretical Basis of the Discrete Element Method,” in *Proceeding of the International Conference on Numerical Methods in Engineering: Theory and Applications*, NUMETA 85, Balkema, A. A. ed., Rotterdam, 897-906.

Yang, C. T., and Hsieh, S. H. (2005). “An Object-Oriented Framework for VEsatile Discrete Objects Simulation Using Design Patterns,” *Computational Mechanics*, 36(2), 85-99.

Yang, F. L., Chang, W. T., Huang, Y. T., Hsieh, S. H., and Chen, C. S. (2013). “Dry Granular Avalanche Down A Flume: Choice of Discrete Element Simulation Parameters,” *Physics of Fluids* 25(12), Paper No. 123303.