EVOLUTIONARY DESIGN FOR BLAST OF STEEL STRUCTURAL SYSTEMS

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ABSTRACT: This paper introduces a novel concept of evolutionary design for blast of steel structural systems. It provides both conceptual and computational frameworks for conducting automated concept generation, analysis, dimensioning, and optimization. The proposed concept has been developed through the integration of various results from previous research on evolutionary design, structural analysis using the finite element method, and computer simulations of blast utilizing computational fluid dynamics.

The paper describes the architecture and individual components of the computer system implementing the proposed concept. The system has been built upon the evolutionary design platform developed at George Mason University. In the developed system, blast loads have been determined using FEFLO, an advanced computational fluid dynamics system created in the Center for Computational Fluid Dynamics at GMU. Structural design and optimization is conducted by Emergent Designer, an integrated research and design support tool developed by the first author. The analysis is performed by ABAQUS, an advanced system for finite element analysis, which allows the explicit structural analysis and evaluation of dynamic behavior of steel structural systems under blast loads when nonlinear behavior of materials and structure is considered.

The developed system enables automatic generation of parameterized designs both at the conceptual and detailed design levels. This was achieved through fully parameterized and object-oriented interfaces connecting major components of the system. This full parameterization facilitates automatic parameterized 3D finite element model generation from the level of dimensions of sketches defining cross-sections of structural members to the level of 3D assemblies of solid parts representing entire structural systems.

KEYWORDS: structural design, blast effects, evolutionary computation, finite element analysis, engineering software.

1 INTRODUCTION

In recent years, there has been a growing interest in finding better ways of protecting our built infrastructure systems against terrorist attacks, particularly in the case of federal buildings and office buildings owned by large private corporations. Such attacks will cause loses of human lives, may create a negative psychological and political impact, and they will be very costly to mitigate. Also, terrorist attacks on federal or private office buildings may disrupt operations of federal agencies or corporations attacked with various short- and long-term consequences.

Terrorists employ asymmetric measures, that means threats that are directed against infrastructure vulnerabilities and weaknesses while ignoring its strengths. To counter such threats, a design paradigm change is necessary. Instead of “traditional” uniform reinforcement of existing or being designed infrastructure systems, the focus should be on understanding terrorist threats in the context of specific systems and addressing these threats in the design process. That can be accomplished through research on terrorist threats to infrastructure systems and through the utilization of results of research on evolutionary designing. In this way, the asymmetric nature of terrorist threats will be, at least partially, counterbalanced by our modern design tools. Such tools enable designers to deal with the complexity of the problems and enhance their search capabilities for innovative design concepts.

In (Arciszewski et al. 2003) a concept of proactive design of infrastructure systems for security has been proposed. In this case, potential terrorist threats are represented by terrorist scenarios. The design is conducted as a coevolutionary process in which terrorist scenarios coevolve with designs for security. When the entire design process is conducted under reasonable assumptions regarding the terrorist threats, its results should represent a rational response to terrorist threats through the design of an infrastructure system, which should properly behave under a spectrum of terrorist threats represented by various terrorist scenarios considered. One of the key concepts is that of a terrorist scenario. It is understood as a feasible combination of decisions to be taken by a terrorist attack planner that may lead to a terror act, i.e. to an event interrupting or negatively impacting the operations of a given infrastructure system. A terrorist scenario can be formally described as a combination of symbolic attributes and their values, each related to a specific terrorist decision.

Unfortunately, in the case of existing office buildings counterterrorism measures, particularly those related to the reinforcements of the existing structural systems, are very difficult to implement and they are not the subject of our interest. We are therefore focused on proactive design of steel structural systems in office buildings. In this case, by proactive design we mean a structural design process in which a structural system is designed satisfying not only standard loads requirements (gravity and wind loads, earthquake forces, etc.) but also considering a number of terrorist scenarios. In the conducted research, we consider terrorist scenarios dealing with explosives and blasts. In the paper, we report our preliminary results for a single terrorist scenario, when a single blast occurs outside the office building in a distance of 13 ft. This is a situation when a car bomb is exploded outside a building. It is a specific case of proactive design, called "evolutionary design."

The paper's objective is to report preliminary results of research on evolutionary design for blast of steel skeleton structures in office buildings. The paper provides the developed computational framework, including its architecture as well as system implementation and integration. Initial results are also reported including the description of the conducted analysis and numerical results regarding displacements under blast conditions of a rigid frame with four types of beam-to-column connections. An example of blast induced deformations of the considered frame is also provided.

2 EVOLUTIONARY COMPUTATION IN STRUCTURAL DESIGN

Evolutionary computation (EC) is a modern search method which utilizes computational models of biological processes of evolution and natural selection encoded in evolutionary algorithms (EAs) to solve complex problems in engineering and science (De Jong 2006). EC also has a relatively long history in structural engineering. Early work on evolutionary structural design dates back to the 1980s and initial applications to sizing and shape optimization of relatively simple structural systems (e.g., trusses (Goldberg and Samtani 1986; Hajela 1990) and frames (Grierson and Pak 1993)). The progress in the fields of evolutionary computation and information technology resulted in applications to more complex and computationally intensive structural design problems, including the topology optimization of discrete-member trusses (Shankar and Hajela 1991), topology optimization of truss structures in pylons (Bohnenberger et al. 1995), and topology, shape, and sizing optimization of truss structures (Rajan 1995). Evolutionary-based topological optimum design of steel structural systems in tall buildings was initially studied in (Arciszewski et al. 1999; 2001) and later extended in (Kicinger et al. 2005c).

A comprehensive survey of evolutionary computation in structural design, including the discussion on current research progress and most promising directions of future research in this field, can be found in (Kicinger et al. 2005b).

3 COMPUTATIONAL FRAMEWORK

The above described concept of evolutionary design for blast has been embedded in a computational framework and subsequently implemented in a computer tool. This was achieved through the integration of several advanced computational models, methods, and tools from the fields of computational fluid dynamics, finite element analysis, and evolutionary computation. In this section, we describe the overall architecture of the computational framework and well as its implementation in a computer tool.

3.1 *Framework architecture*

The overall architecture of the computational framework is presented in Figure 1.

Figure 1 shows that the framework consists of three major computational components:

- Evolutionary Computation Component,
- Finite Element Analysis Component, and
- Computational Fluid Dynamics Component

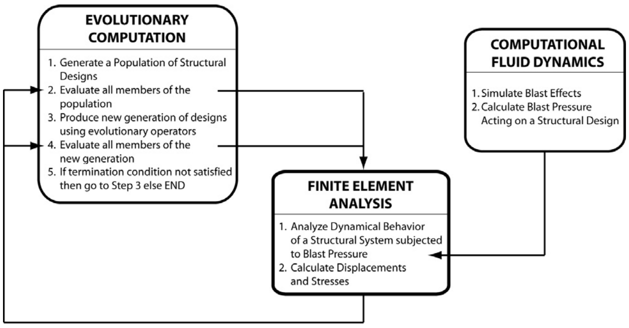

Figure 1. Architecture of the computational framework for evolutionary design for blast.

Evolutionary Computation Component conducts the actual evolutionary design processes in which optimal designs of steel structural systems subjected to blast loads are sought. In these evolutionary design processes, the quality of each generated structural design needs to be evaluated. This is done by the Finite Element Analysis Component which simulates dynamical behavior of a structural system subjected to blast loads. The blast pressures are calculated by the Computational Fluid Dynamics Component which simulates the blast effects for a given amount of explosives located a given distance from the office building (the amount of explosives and the distance from the office building are parameters of a computational experiment). The end results of blast simulation include the time-and-space dependent blast pressures acting on the structural system and these are subsequently incorporated in the structural analysis conducted by the Finite Element Analysis Component.

The details of the implementation of this computational framework are presented in the following subsection.

3.2 *System implementation*

The details of the implementation of the computational framework for evolutionary design for blast are presented in Figure 2. It shows that the evolutionary design of steel structural systems in office buildings subjected to blast loads is conducted by Emergent Designer (Kicinger et al. 2005a) which is in turn powered by ECJ (Luke 2006), an open-source evolutionary computation library. Evolutionary design for blast constitutes a separate module of Emergent Designer in which symbolic and numerical representations of steel structural systems of office buildings are defined. Emergent Designer enables either single- or multi-objective design optimization of steel structural systems under blast loads.

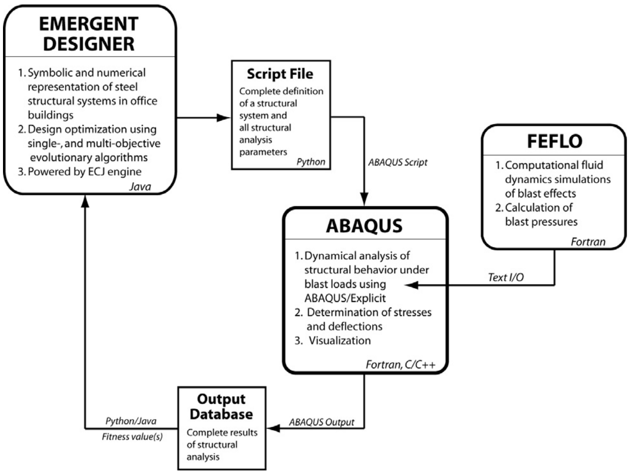

Figure 2. Implementation of the computational framework for evolutionary design for blast.

Each structural design, represented during the evolutionary design process by a fixed-length genome, needs to be evaluated. In order to do that each genome is translated into a finite element model of a steel structural system. This is achieved by the integration of Emergent Designer with ABAQUS (ABAQUS Inc. 2004), one of the leading finite element analysis systems. This integration is supported by the developed Python package consisting of several modules. The Python package facilitates the translation of the genome into a 3D finite element model of steel structural system. As a result a Python script file is produced which follows ABAQUS scripting guidelines and hence can be read directly by ABAQUS kernel. This script file also contains all parameters (i.e., dead, live, and wind loads as well as material definitions) necessary to conduct analyses of dynamical behavior of structural systems using ABAQUS/Explicit.

In the pre-processing phase of structural analysis, ABAQUS reads the time-and-space dependent values of blast pressures acting on a steel structural system. These values of blast pressures are produced by FEFLO (Löhner et al. 2002), an advanced computational fluid dynamics system developed by the Center for Computational Fluid Dynamics at George Mason University. When ABAQUS/Explicit completes the finite element analysis of a steel structural system, it stores the results in an output database. This database contains all relevant information about the stresses, deformations, etc. and hence provides complete description of the dynamical behavior of a steel structure subjected to blast loads. Next, Emergent Designer uses another Python script to extract one or more fitness values from the output database, depending whether single- or multi-objective optimization of steel structural systems is performed. These value(s) are subsequently assigned to the genome and the entire evaluation process repeats for another genome in the population of structural designs.

3.3 *System integration*

The integration of Emergent Designer and ABAQUS briefly described in the previous subsection offers advanced functionality for conducting evolutionary design processes at both conceptual design and detailed design of levels. In particular, the developed Python package was designed to facilitate design processes at both levels through:

a. Automatic generation of parameterized sketches of cross-sections of structural members, including I-sections and box sections
b. Support for solid and shell finite elements
c. Automatic generation of 3D solid parts based on parameterized sketches
d. Automatic assignment of material properties for generated structural members (currently, only steel definition is supported)
e. Automatic division of 3D solid parts into regions and cells to define optimal finite element meshes
f. Automatic detection of element surfaces to which interaction conditions are applied
g. Automatic creation of ABAQUS assemblies (3D models consisting of structural member instances)
h. Automatic applications of boundary conditions and blast loads
i. Automatic mesh generation of the entire structural system with the mesh-size provided as a parameter of the model
j. Automatic creation of ABAQUS Explicit analysis jobs and their evaluation by ABAQUS Kernel.

All this functionality facilitates seamless integration of evolutionary design process and advanced finite element analysis of 3D models of steel structural systems.

At the current stage of system development, computational fluid dynamics analyses using FEFLO are conducted before the actual evolutionary design processes. Their results (blast pressures acting on a steel structural system) are saved in an output file which is subsequently read by ABAQUS during the process of structural analysis of the dynamical behavior of the steel frame. Each blast simulation conducted by FEFLO is defined by two major parameters: the amount of explosives used and the distance from the office building. In this way, the results of computational fluid dynamics analyses generated for various combinations of these two parameters form a library of blast loads which can be utilized during the structural analysis of steel frames conducted by ABAQUS.

4 INITIAL RESULTS

As the research project described in this paper is in its initial stages, only preliminary results have been produced. In this section, we describe initial results of relative performance analysis of 4 types of joints in steel structural systems under blast loads. The goal of these computational experiments was to evaluate the feasibility of the approach described in the previous sections and to determine the appropriate types of finite elements, mesh generation methods, and types of structural analysis for the evolutionary design for blast.

The initial analysis has been conducted for a three-bay and eight-story steel frame shown in Figure 3. The frame was subjected to a blast on the ground level in the distance of 13 ft from the building. Blast loads have been calculated by FEFLO for a period of 500 ms as shown in Figure 4 . Material definition for structural steel has been assumed as in Figure 5 in accordance to the ABAQUS analysis manual (ABAQUS Inc. 2004). However, a more appropriate material definition is currently being sought.

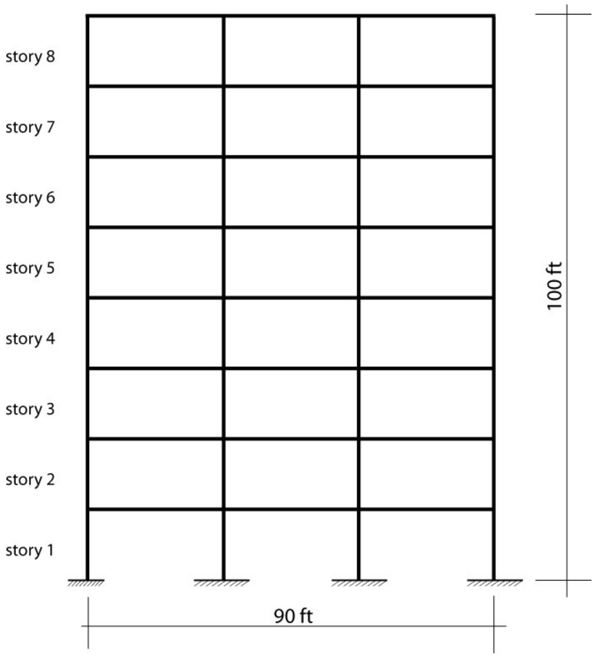

Figure 3. Topology of the steel frame considered in the initial experiments.

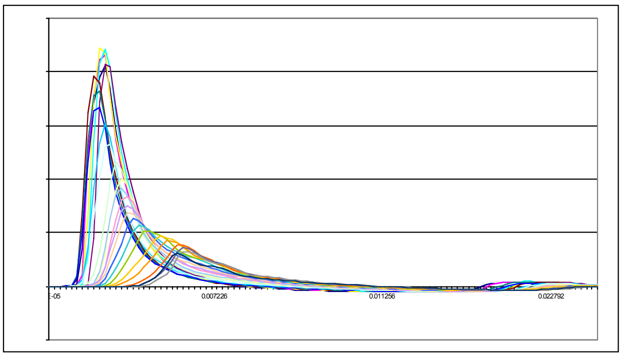

Figure 4. Blast pressure diagram displaying time-dependent pressure values for various locations along the frame height.

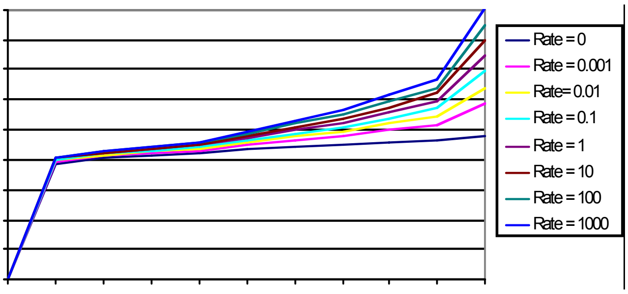

Figure 5. Material definition for steel assumed in the initial finite element analysis.

In the conducted relative comparisons, four types of joints have been analyzed (see Figure 6) including:

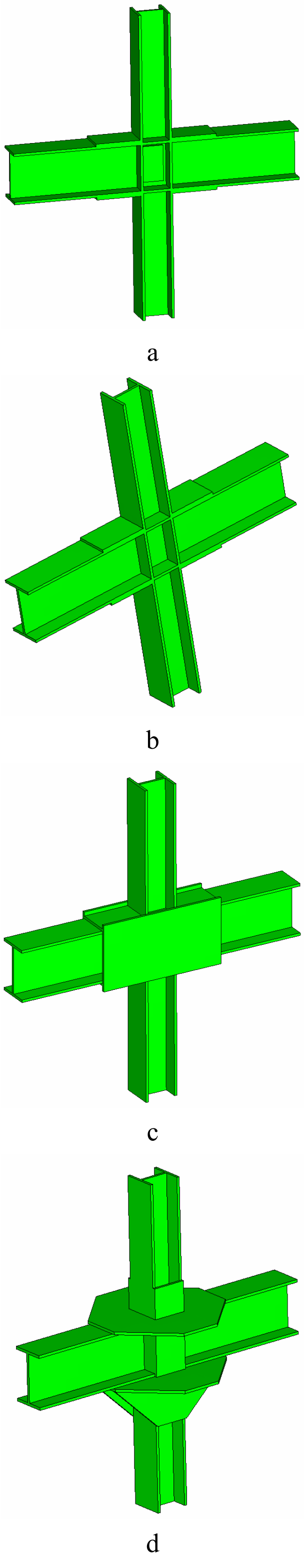

Figure 6. Four analyzed joints: standard joint (a), modified standard joint (b), Side-Plate joint (c), and TA joint (d).

- “standard” rigid joint
- “modified standard” rigid joint
- “Side-Plate” rigid joint
- “TA” rigid joint

The modified standard rigid joint has been proposed by Ph.D. student Paul Gebski. It has an additional vertical plate, or plates, added to the column web within the joint.

TA joint is a 3D prefabricated joint, patented by the third author in 1976.

In the reported analysis, solid C3D8R ABAQUS finite elements were used (continuum/solid 3D elements with 8 nodes and with reduced integration). The models of steel frames with compared joints consisted of 33,340, 36,808, 41,538, and 45,696 finite elements, respectively. The conducted analysis included the comparison of the stress and strain distribution, of displacements and of the support reactions, including both horizontal and vertical reactions. An example of strain distribution for a model with standard joints for the region close to the blast is shown in Figure 7, which also reveals the nature of the frame's deformations.

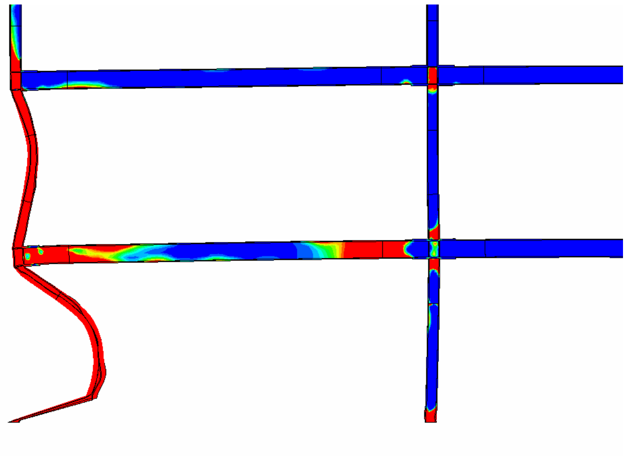

Figure 7. Strain distribution for a model with standard joints for the region close to the blast.

The comparison of maximum horizontal displacements (sway) of the structure under blast loads is provided in Table 1. It shows maximum displacement values for two characteristic points of the structural system (left and right top corners) for all four types of joints. As only initial computational experiments have been conducted, the results presented in Table 1 should be considered only in qualitative terms, i.e., they show relative differences among the four joint types rather than the actual numerical values.

Table 1. Comparison of max. horizontal displacements of the structure for four types of joints.

Joint Type	Left side building max displacement [m]	Right side building max displacement [m]
Standard	22 cm	13,5 cm
Pawel	17 cm	10,1 cm
SidePlate	28 cm	16,9 cm
Tomasz Arciszewski	21 cm	13 cm

5 CONCLUSIONS

Structural design for security is becoming an important component of structural design. In particular, design for blast of steel structural systems in office buildings is especially important, because such buildings may particularly attract terrorist attacks. The reported research is in early stages, but it has already revealed the complexity of the problem and its computational difficulty. The proposed proactive design for security is feasible, but at present only its simplified version, i.e. evolutionary design for blast, has been actually implemented and conducted.

In this paper, the developed computational framework for evolutionary design for blast was introduced and the architecture of its actual implementation discussed. A particular emphasis has been put on addressing integration issues among major components of the framework: Evolutionary Computation Component, Finite Element Analysis Component, and Computational Fluid Dynamics Component.

The paper also presents initial results of comparative analyses of four joint types for steel structural system conducted using the developed framework. Even though the results are only preliminary, they show the feasibility of the proposed method.

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