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FURTHER DEVELOPMENT AND APPLICATION OF DATA MODEL FOR LARGE-SCALE STRUCTURAL EXPERIMENTS

by

Stanley King

A Thesis
Presented to the Graduate and Research Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science

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Civil Engineering

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Date

Dr. Richard Sause
Thesis Advisor

Dr. Stephen Pessiki
Chairperson of Department

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Abstract

The information and data related to the large-scale structural experiments are often complicated and contained in various documents, drawings, photos, and other computer-based files. A data model is needed to efficiently access, share, and use the information and data. The Lehigh Model was developed by Lee et al. (2006) at the Real-Time Multi-Directional (RTMD) earthquake simulation facility at the ATLSS Center at Lehigh University. The development of the Lehigh Model was based on a review of previous work on data models and databases for structural experiments and a study of a number of large-scale structural experiments conducted at the ATLSS Center. The primary class hierarchy of the Lehigh Model consists of the project class level, the experimental task class level, the test condition class level, the test class level, and the data set level. Based on the earlier Lehigh Model, updated versions of the classes and attributes of the Lehigh Model are presented to better represent the information and data for large-scale structural experiments conducted at the RTMD earthquake simulation facility.

The Lehigh RTMD Metadata Web is an implementation of the updated Lehigh Model. Two examples of applying the Lehigh RTMD Metadata Web are presented. The first example is the Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems project. The second example is the Studies on Large-scale, Real-time Pesudodynamic (PSD) Testing project, which focuses on hybrid earthquake simulation.

Chapter 1

Introduction

1.1 Overview

Structural researchers perform laboratory experiments to examine and understand the performance of structural components, connections, and assemblies and to develop ways of enhancing this performance. Often these experiments are conducted at large-scale on complex structural assemblies. The experiments may involve one or more test methods, including quasi-static, pseudo-dynamic, or hybrid pseudo-dynamic test methods, to closely simulate realistic loading conditions. The results from these experiments are published in papers and reports, shared with other researchers, and used for related research and practical applications.

The large amount and the diversity of the information related to structural experiments, including data files, drawing files, photos, videos, researcher's notes, and other descriptions of the test specimens, test facility, test methods, and test fixtures, make it difficult to efficiently access, share, and use the information. The relationships among the different types of information (e.g., among the test data, the drawings for different specimens, photos of different tests, and the test methods employed in different tests) are often unclear and perhaps misleading to others who may try to use the data after the experimental research project is complete. In addition, organized (structured) searches to locate specific elements of the information are often impossible. Even the research team who conducted the experiments may not be able to efficiently access all of the details of

this information. As a result, while the main concepts from the structural experiments are disseminated in papers and reports, many interesting and important details of the experiments may not be readily available or easily shared.

A data model for structural experiments can be used to organize and represent the related information and data. A data model helps researchers logically organize and manage the information and data from structural experiments using predefined hierarchies and categories of information. The logical organization of the information enables relationships among information to be established, enables missing information to be identified, and enables structured searches to locate specific elements of the information. Once the data model is implemented, the implemented model provides structural researchers with a convenient means to access, share, and use the information. If the implemented model can be accessed through the internet, then a wide range of researchers and practitioners can access and use the results from the structural experiments.

1.2 Research Objectives

This research is based on an earlier Lehigh Model developed by Lee et al. (2006). The objectives of this research are to further develop the classes and attributes of the Lehigh Model and to study and present an implementation of the Lehigh Model in a web-based data base (Marullo, 2007). This is to be accomplished by:

- To improve the classes and attributes of the Lehigh Model for large-scale structural experiments, including typical experiments and hybrid experiments.
- To present an implementation of the Lehigh Model, named the Lehigh RTMD Metadata Web, by introducing concepts of the implementation and illustrating its interface.
- To illustrate the implementation using examples of structural experiments conducted at the Real-Time Multi-Directional (RTMD) earthquake simulation facility in the ATLSS Center at Lehigh University.

1.3 Outline

This thesis starts with the present chapter, which outlines the need for a data model for large-scale structural experiments. Chapter 2 presents the notation used to represent the classes and attributes of the Lehigh Model. The basic organization of the Lehigh Model is also presented. Chapter 3 presents the classes and attributes of the earlier Lehigh Model and the updated classes and attributes of the Lehigh Model. Chapter 4 presents a web application, named the Lehigh RTMD Metadata Web, which is an implementation of the Lehigh Model. Chapter 5 presents an example applying the Lehigh RTMD Metadata Web to a typical experiment and Chapter 6 present an example applying the Lehigh RTMD Metadata Web to a real-time hybrid experiment. Chapter 7 summarizes this thesis, provides conclusions, and makes suggestions for future work.

Chapter 2

Overview of Lehigh Model

2.1. Introduction

This chapter presents the notation used to represent the classes and attributes of the Lehigh Model. The development of the Lehigh Model for large-scale structural experiments is summarized. The primary class hierarchy of the Lehigh Model is then presented.

2.2. Notation for Classes and Attributes of Lehigh Model

The Lehigh Model consists of classes and attributes as shown in Figure 2.1. The classes and attributes are represented using a modified entity-relationship diagram developed for entity-based integrated design product and process models by Hong and Sause (1994). Each rectangular box shown in Figure 2.1 indicates a category of entities (referred to as an entity category or a class). Each attribute of a class is shown below the rectangular box with a horizontal bar. At end of each horizontal bar, a circle is attached to identify the value of the attribute. If the attribute is single-valued, the bar ends with an empty circle, and if the attribute is multi-valued, the bar ends with a solid circle. The value set of an attribute (the set of possible values for the attribute) is represented in square brackets. The attribute type is identified in parentheses below the bar. Attributes are classified into two main types: (1) “data-valued” attributes (DVA) whose values are alphanumeric or are otherwise indecomposable; and (2) “object entity-valued” attributes (OEVA) whose values refer to other classes. Further classifications of the attributes

include base attributes (B), internally derived attributes (DI), and externally derived attributes (DE). Some of these attribute types are used in the data model figures in this thesis.

2.3. Development of Lehigh Model

Previous work on data models and databases for structural experiments was considered during the development of the Lehigh Model. The Reference NEESgrid Model (Peng and Law, 2004), the Oregon State Model (Oregon State University, 2003), and the NEEScentral Model (NEESit, 2006) were reviewed (Lee et al., 2006). These models are shown in Figures 2.2, 2.3 and 2.4, respectively. These three data models provided insight into appropriate classes and attributes for the Lehigh Model. Two existing databases of structural experiment data, the SAC Design Information Database (http://www.sacsteel.org/, 2006) and the PEER Structural Performance Database (http://nisee.berkeley.edu/spd, 2006) were studied (Lee et al., 2006). These databases enable searches, based on certain types of data, to be conducted to retrieve data from the databases. The “searchable fields” of these databases, shown in Figure 2.5 (a) and (b), suggest the types of information associated with structural experiments that should be included in the Lehigh Model.

A number of large-scale structural experiments conducted at the Real-Time Multi-Directional (RTMD) earthquake simulation facility were also studied. The information and data related to these experiments suggested the primary classes and attributes of the Lehigh Model. Based on the previous work mentioned above and

studies of experiments conducted at the ATLSS Center, the Lehigh Model was formulated to represent the information and data associated with large-scale structural experiments. An earlier report on the Lehigh Model (Lee et al., 2006) explains in more detailed information how the previous work and studies of experiments were considered in the development of the Lehigh Model.

2.4. Primary Class Hierarchy of Lehigh Model

The primary class hierarchy of the Lehigh Model consists of five main levels as shown in Figure 2.1, namely, the project class level, the experimental task class level, the test condition class level, the test class level, and the data set class level. The information and data for experiments are classified into these class levels in the Lehigh Model. The definitions of the class levels and the relationships between the class levels are described below:

Project Class Level

The project class level is at the highest level in the Lehigh Model. This level includes the project class to represent fundamental information about structural research projects, such as objectives, project scope, summarized conclusions, associated organizations, and the experiments and/or analyses performed. As shown in Figure 2.1 a project class has two multi-valued attributes for experimental tasks and analysis tasks, respectively.

Experimental Task Class Level

This level represents the experiments and the analyses conducted under a specific project. Two main classes are included at this level as shown in Figure 2.1, namely, the experimental task class and the analysis task class, which are the value sets of the attributes of the project class. Information related to experimental tasks and analytical tasks are included in these classes.

The experimental task class is a generalization of the typical experimental task class and the hybrid experimental task class. The typical experimental task class represents experiments using typical methods for structural tests, such as the quasi-static method and the pseudo-dynamic method. The typical experimental task class shown in Figure 2.1 has a multi-valued attribute for test conditions to represent the experimental setup. The hybrid experimental task class represents experiments using the hybrid pseudo-dynamic method; either a local hybrid experiment or a distributed hybrid experiment. The hybrid experimental task class shown in Figure 2.1 includes a single-valued attribute for simulation coordinator and two multi-valued attributes for analytical substructures and physical substructures, which represent hybrid experimental setups based on the substructuring technique (Dermitzakis and Mahin, 1985).

The analysis task class represents numerical simulations which are independent of any experimental task under a project. The analysis task class shown in Figure 2.1 includes a multi-valued attribute for analysis conditions to represent the details of analyses that are conducted.

Test Condition Class Level

This level represents the details of experimental setups, which includes physical and analytical setups. Because of the varied test methods considered, an experiment task (as well as an analysis task) consists of one or more different types of experimental setups.

The test condition class is the value set of the test conditions attribute of the typical experimental task class as shown in Figure 2.1. The test condition class represents the laboratory conditions for typical experiments. The class includes information on the specimen, facility, loading fixtures, bracing and reaction fixtures, sensors, and cables which are the main components of experimental setups. A multi-valued attribute for tests is included in the test condition class to represent the test protocols and resulting test data.

Because of the complexity of a hybrid experimental task, three classes are need to represent the experimental conditions, namely, the simulation coordinator class, the analytical substructure class, and the physical substructure class, which are the value sets of the attributes of the hybrid experimental task class as shown in Figure 2.1. The simulation coordinator class represents information on the simulation model, software, and simulation facility used to run the simulation. The analytical part of a hybrid experimental task is represented by the analytical substructure class which includes information on the analytical substructure model, software, and facility used to run the analytical simulation. The physical part of a hybrid experimental task is represented by the physical substructure class which includes information on the laboratory conditions

which is similar to the test condition class. Three multi-valued attributes for simulations, analytical substructure computations, and physical substructure tests are included in the simulation coordinator class, the analytical substructure class, and the physical substructure class, respectively, to represent the data from a hybrid simulation.

In Figure 2.1, the analytical conditions of an analysis task are represented by the analysis class, which is the value set of the analysis conditions attributes of the analysis task class. The analysis class includes information on the software and model used in the analysis. The analysis class has a multi-valued attributes for analysis cases to represent the data from the analyses.

Test Class Level

This level represents loading conditions, such as history files, simulation method files, data acquisition system configuration files, controller configuration files, and input files for experiments and analytical simulations. In Figure 2.1, the classes at this level are the test class, the simulation class, the analytical substructure computation class, the physical substructure test class, and the analysis case class. These classes are the value sets of the attributes of the test condition class, the simulation coordinator class, the analytical substructure class, the physical substructure class, and the analysis class, respectively. All of these classes have a single-valued attribute to represent either the experimental data set or the analytical data set resulted from the experiment or analysis.

Data Set Level

The results of experiments and analytical simulations are represented at this level. The abstract data set class in Figure 2.1 represents common attributes of the experimental data set class and the analytical data set class. As shown in Figure 2.1, the experimental data set class includes raw data and corrected data from a test or from a physical substructure test; the analytical data set includes output data from a simulation, an analytical substructure computation, or an analysis case.

2.5. Summary

This chapter presents an overview of the Lehigh Model. The notation used for the classes and attributes of the Lehigh Model is described. The development of the Lehigh Model is based on previous work on data models and databases for structural experiments, as well as studies of experimental projects conducted at the RTMD earthquake simulation facility. The class hierarchy of the Lehigh Model includes five main levels, namely, the project class level, the experimental task class level, the test condition class level, the test class level, and the data set class level. These class levels are described. This chapter only presents on part of the classes and attributes of the Lehigh Model. The complete classes and attributes of the Lehigh Model are presented in Chapter 3 and in the report by Lee et al. (2006).

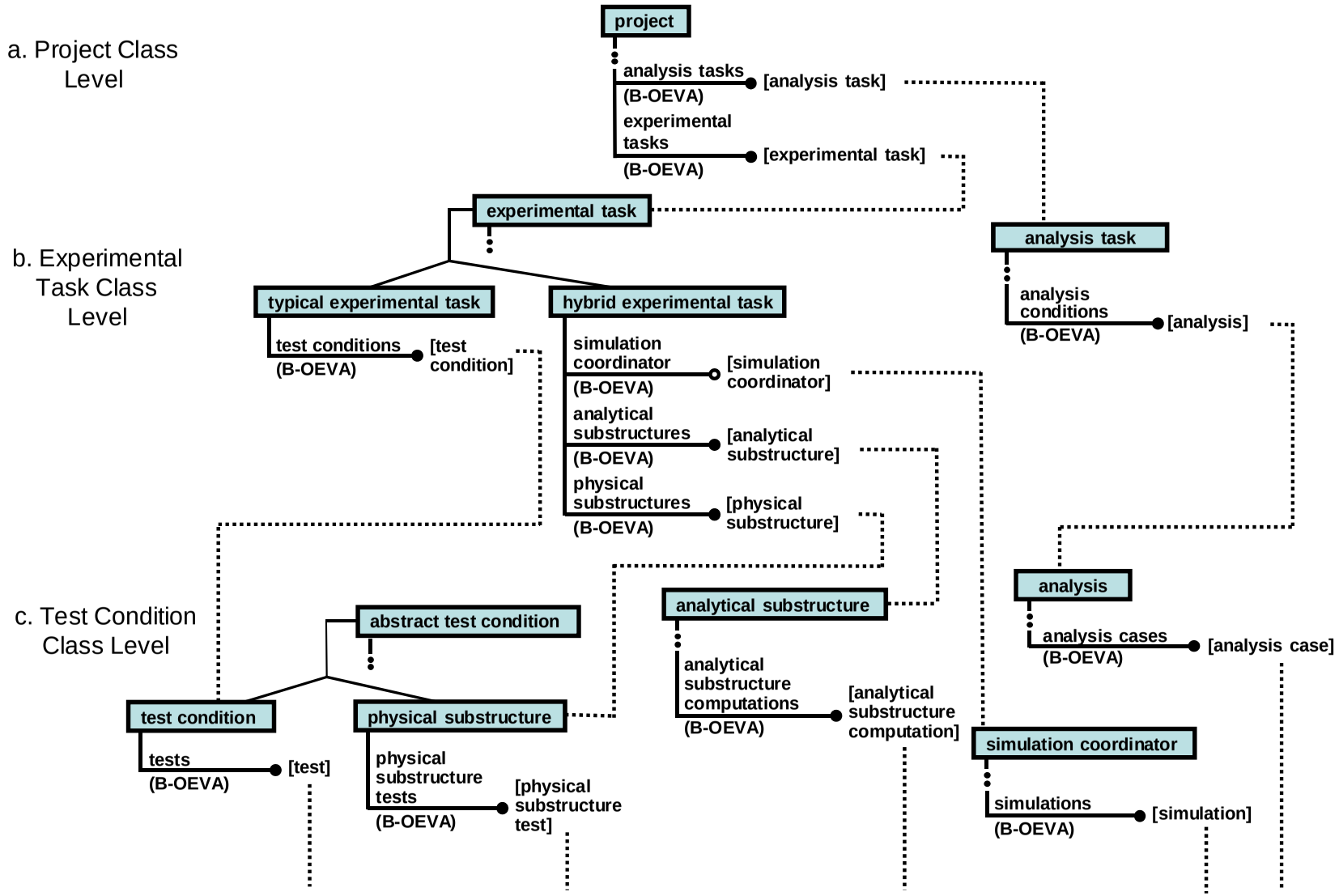


Figure 2.1 Levels of Classes in Class Hierarchy (Adopted from Lee et al., 2006)

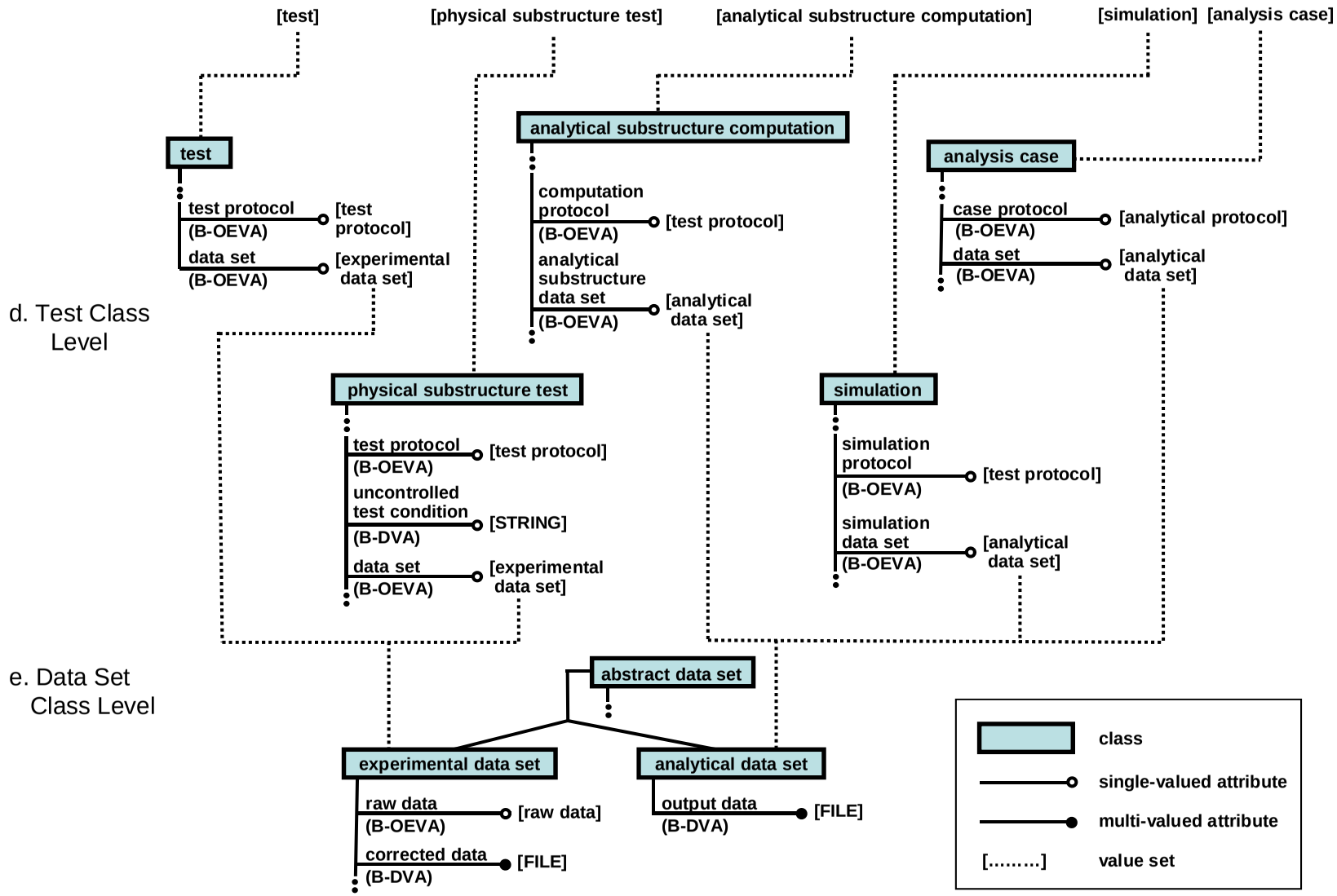


Figure 2.1 Levels of Classes in Class Hierarchy (Adopted from Lee et al., 2006) (Continued)

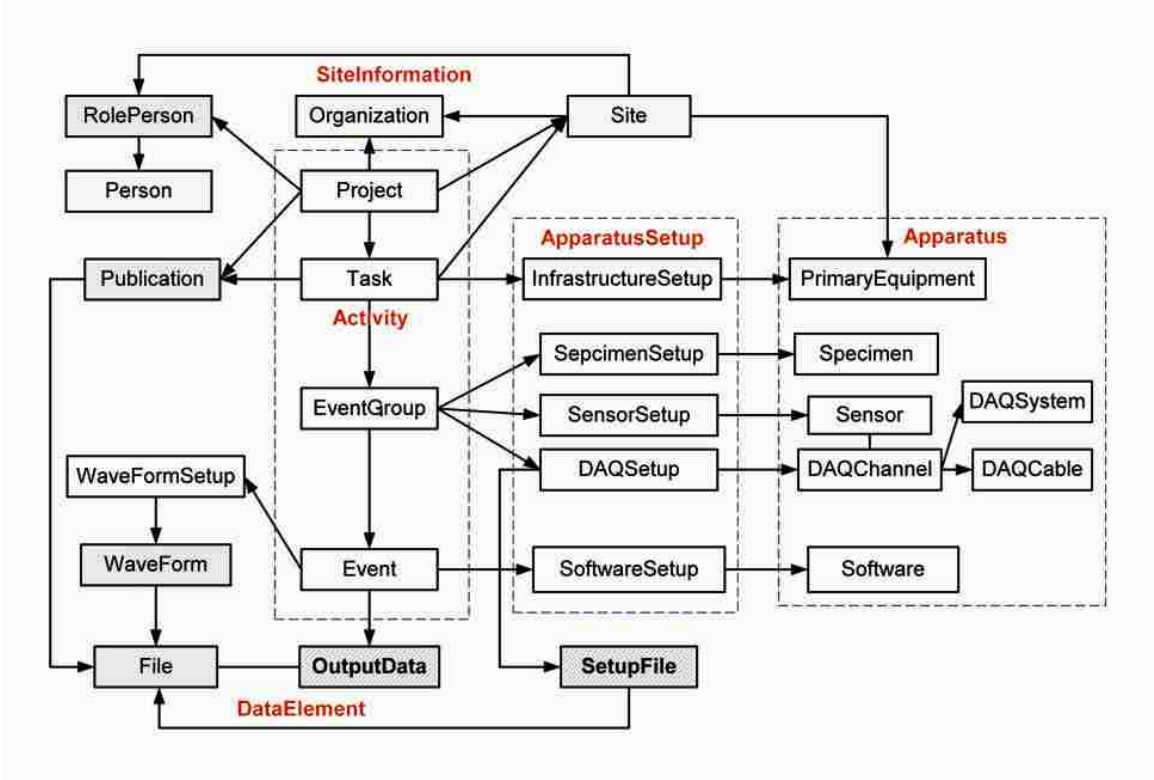


Figure 2.2 Reference NEESgrid Model (Peng and Law, 2004)

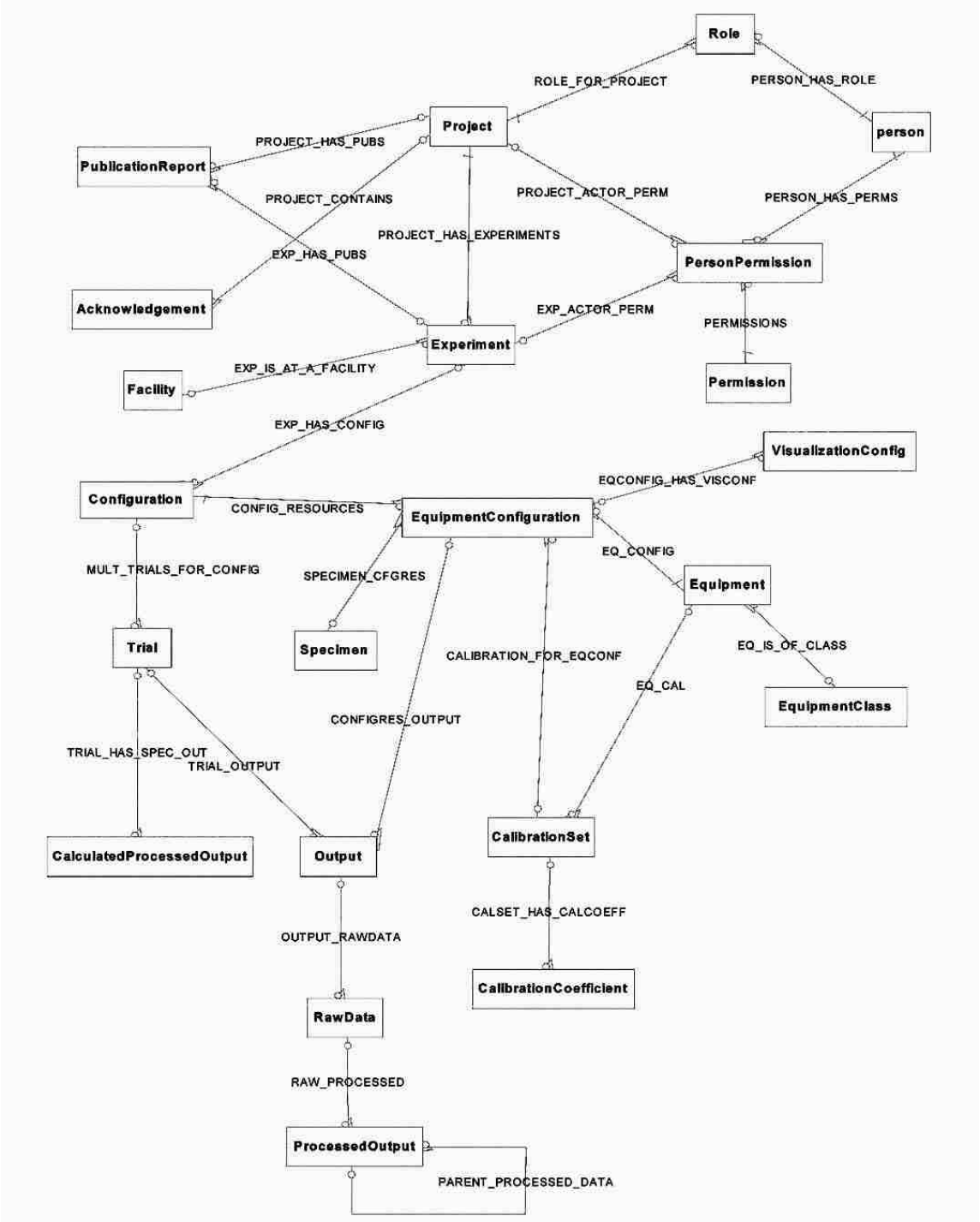


Figure 2.3 Oregon State Model (Oregon State University, 2003)

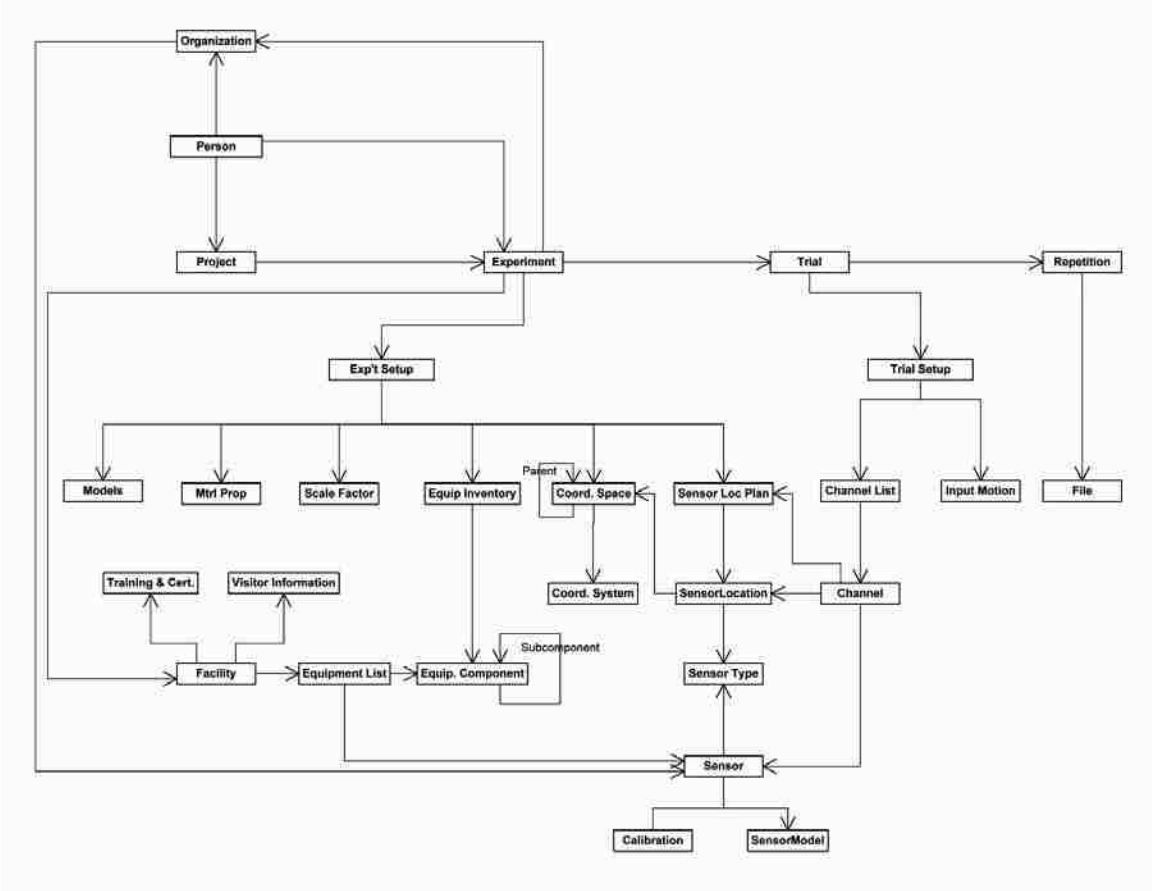
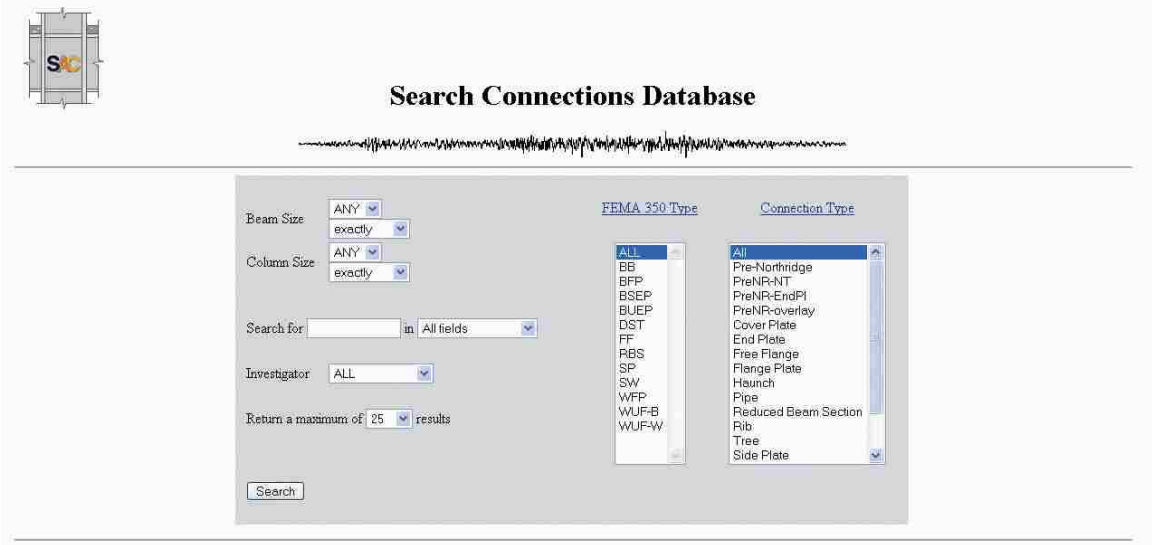


Figure 2.4 NEEScentral Model (NEESit, 2006)



(a) SAC Design Information Database (http://www.sacsteel.org/, 2006)

(b) PEER Structural Performance Database (http://nisee.berkeley.edu/spd/, 2006)

Figure 2.5 Databases for Structural Test Data

Chapter 3

Update of Lehigh Model

3.1. Introduction

This chapter presents a brief introduction of the earlier Lehigh Model, which was developed by Lee et al. (2006). The recently updated classes and attributes of the Lehigh Model are then presented.

3.2. Earlier Lehigh Model

An earlier version of the Lehigh Model was developed by Lee et al. (2006). This earlier Lehigh Model mainly focused on typical and hybrid experiments. The classes and attributes of this earlier model are displayed in Figure 3.1 to 3.8. Figure 3.1 shows the project class, which is at the highest level of the model to represent fundamental information on a structural research project. The value set of the experimental tasks attribute of the project class refers to the experimental task class, which is a generalization of the typical experimental task class and hybrid experimental task class as shown in Figure 3.1. These two classes represent information on the typical and hybrid experiments.

The test condition class shown in Figure 3.1 is the value set of the test conditions attribute of the typical experimental task class. Because the test condition class for typical experiments and the physical substructure class for hybrid experiments have common attributes to represent the major components of laboratory conditions, an

abstract class, named the abstract test condition class shown in Figure 3.1, is created to include common attributes inherited from the test condition class and the physical substructure class. Related classes as shown in Figure 3.2 to 3.6, such as the specimen class, the facility class, the loading fixture class, the bracing and reaction fixture class, the sensor class, and the cable class, are the value sets of the attributes of the abstract test condition class. In Figure 3.1, the value set of the tests attribute of the test condition class refers to the test class shown in Figure 3.7. The test class has attributes to represent the test protocol and the resulting data.

Figure 3.8 shows the primary classes to represent information for a hybrid simulation. The simulation coordinator class, the analytical substructure class, and the physical substructure class represent part of a hybrid experimental setup. For each hybrid experimental setup, a number of simulations, analytical substructure computations, and physical substructure tests can be made as shown in Figure 3.8. The relationship among a simulation, related analytical substructure computations, and related physical substructure tests for a hybrid simulation is represented by the simulation substructure interface class, which is the value set of the corresponding attributes of the simulation class, the analytical substructure computation class, and the physical substructure test class as shown in Figure 3.8.

3.3. Updated Classes and Attributes of Lehigh Model

3.3.1. Project and Experimental Task Classes

Updated project and experimental task classes are presented in Figure 3.9. The organizations attribute is moved from the experimental task class shown in Figure 3.1 into the updated project class shown in Figure 3.9 because a project is sponsored and conducted by a number of organizations. An attribute for analyses is moved from the abstract test condition shown in Figure 3.1 into the updated experimental task class shown in Figure 3.9 as a common attribute for typical experimental tasks and the hybrid experimental tasks so that the analyses attribute can describe one or more numerical analyses that correspond to a structural experiment with a specific experimental setup and loading method. In this new location, numerical analyses used to design the experiment can also be represented by this analyses attribute.

3.3.2. Abstract Test Condition Class

Figure 3.9 also displays the updated attributes of the abstract test condition class. The attributes for DAQ systems, controller systems, and simulation systems in the abstract test condition class shown in Figure 3.1 are removed, since the configuration files for these systems may be different for various tests performed in a given experimental setup. These attributes are moved to the test protocol class described in the following section. The attribute for analyses in the abstract test condition class shown in Figure 3.1 is moved to the updated experimental task class shown in Figure 3.9 because changes in laboratory conditions may not affect the numerical simulation (i.e., a numerical simulation can represents a number of different test conditions), and also some analyses

used to design an experiment may not correspond to a specific laboratory condition. The rest of the attributes of the test condition class are the same as described in the earlier report (Lee et al., 2006).

3.3.3. Test Protocol Class

The updated test protocol class is presented in Figure 3.10 to represent the loading conditions for an experiment. The test protocol class is the value set of the test protocol attribute of the test class shown in Figure 3.10 for typical experiments, and is also the value set of corresponding attributes of the simulation class, the analytical substructure computation class, and the physical substructure test class as shown in Figure 3.11 for hybrid experiments. As shown in Figure 3.10, the attributes for the DAQ configuration files and controller configuration files are included in the updated test protocol class to replace the attributes for DAQ systems and controller systems in the abstract test condition class shown in Figure 3.1, because these configuration files, such as the DAQ calibration parameters and controller parameters, may vary for each test protocol. The other configuration files attribute is added in the updated test protocol class to represent other configuration data, such as telepresence and scramnet memory configurations of the Real-Time Multi-Directional (RTMD) earthquake simulation facility.

3.3.4. Data Set Class

Figure 3.10 shows the updated data set class, which is modified from the data set class shown in Figure 3.7 to record experimental results from physical experiments and analytical simulations. The updated data set class shown in Figure 3.10 is an abstract

class of the analytical data set class and the experimental data set class. The analytical data set class is the value set of corresponding attributes of the simulation class, the analytical substructure computation class, and the analysis case class as shown in Figure 3.11. The experimental data set class is the value set of corresponding attributes of the test class and the physical substructure test class as shown in Figure 3.10 and 3.11. The data set class shown in Figure 3.10 includes common attributes inherited from the analytical data set class and the experimental data set class. These common attributes are description, description files, processed data, images, and videos. The analytical data set class includes an attribute for output data to represent the results from analytical simulations. The experimental data set class includes attributes for raw data, corrected data, and web cams to represent the results from physical experiments. The value set of the raw data attribute refers to the raw data class, which includes attributes for binary data and engineering unit data as shown in Figure 3.10. The attribute for corrected data represents the experiment data that must be corrected or revised to compensate for calibration problems, to eliminate noise, to handle zero-offset conditions, or to apply an overall correction factor. The value set of the web cams attribute refers to the web cams class, which includes the attributes for captured images, timelapsed videos, and composite videos as shown in Figure 3.10.

3.3.5. Simulation Coordinator and Simulation Classes

Figure 3.11 shows the updated simulation coordinator class. The simulation coordinator represents the software and computation facility used to conduct/control a hybrid experiment. In order to generate commands to and receive feedback from substructures,

a numerical model is included in a simulation coordinator to run the simulations. The attributes for simulation model and software are added into the updated simulation coordinator class as shown in Figure 3.11. These two attributes describe the numerical model and software used to run the simulations. The value sets of the simulation model and software attributes refer to the model class and the software class shown in Figure 3.13, respectively. These classes are described in the updated analysis class below.

Figure 3.11 also shows the updated simulation class, which is the value set of the simulation attribute of the simulation coordinator class. The descriptive files and persons attributes are added in this updated class as shown in Figure 3.11. The attribute for descriptive files enable researches to describe a simulation by using images or existing documents; the attribute for persons is to record the people who conduct the simulations. As shown in Figure 3.11, the value set of the simulation protocol attribute is changed to refer to the test protocol class, because the test protocol class in Figure 3.10 can also represents the loading conditions used to run the simulations. The value set of the simulation data set attribute is also changed to refer to the analytical data set class in Figure 3.10.

3.3.6. Analytical Substructure Computation and Physical Substructure Test Classes

Figure 3.11 also shows the updated analytical substructure computation class and the updated physical substructure test, which are the value sets of the attributes of the analytical substructure class and the physical substructure class, respectively. The

attributes for descriptive files and persons are also added in these updated classes. As shown in Figure 3.11, the value set of the computation protocol attribute of the analytical substructure computation class is changed to refer to the test protocol class in Figure 3.10 to represent the loading conditions used to run the computations. The value sets of attributes for the data set of the analytical substructure computation class and the physical substructure test class are changed to refer to the analytical data set class and the experimental data set class, respectively.

3.3.7. Analysis Task, Analysis and Analysis Case Classes

The analysis task class is the value set of the analysis tasks attribute of the project class as shown in Figure 3.9. The analysis task class represents numerical simulations for a project, which are independent of other experimental tasks under a project. The class includes attributes for description, descriptive files, publications, and presentations to represent information on an analysis task. A multi-valued attribute for analysis conditions is included in the analysis task class to represent various types of numerical simulations and results.

The updated analysis class shown in Figure 3.12 is modified from the analysis class in Figure 3.7 to describe details of an analytical setup, which include numerical models, computer hardware, and software. The analysis class is the value set of the analysis conditions attribute of the analysis task class and is also the value set of the analyses attributes of the experimental task class as shown in Figure 3.9. As shown in Figure 3.12, the model class represents a numerical model by description, model files, and model

images; the hardware class describes the computer system; the software class describes the software, such as OpenSees, DRAIN -2DX, SAP2000, ABAQUS, and others. These classes are the value sets of the attributes of the analysis class as shown in Figure 3.12. A multi-valued attribute for analysis cases is included in the analysis class, so a number of analysis cases can be executed for a given analytical setup.

Figure 3.12 also shows the analysis case class, which is the value set of the analysis cases attribute of the analysis class. The analysis case class represents a single numerical simulation. The attributes represent the analysis case protocol and the resulting analytical data set. As shown in Figure 3.12, the case protocol class is the value set of the case protocol attribute. The input files attribute of the case protocol class describes the loading conditions for the numerical simulation. The value set of the data set attribute of the analysis case class refers to the analytical data set class as shown in Figure 3.10 to represent the results from a numerical simulation.

3.4. Summary

This chapter presents the earlier Lehigh Model developed by Lee et al. (2006). The earlier model mainly focuses on typical and hybrid experiments. A concise introduction is presented to describe the major classes and attributes of the earlier model. The recently updated classes and attributes of the Lehigh Model are presented. The updated classes are the project class, the experimental task class, the abstract test condition class, the test protocol class, the data set class, the analytical data set class, the experimental data set class, the simulation coordinator class, the simulation class, the analytical substructure

computation class, the physical substructure test class, the analysis task class, the analysis class, the analysis case class, and the case protocol class. Details of the explanation for unchanged classes and attributes of the Lehigh Model can be found in Chapter 4 of the earlier report (Lee et al., 2006).

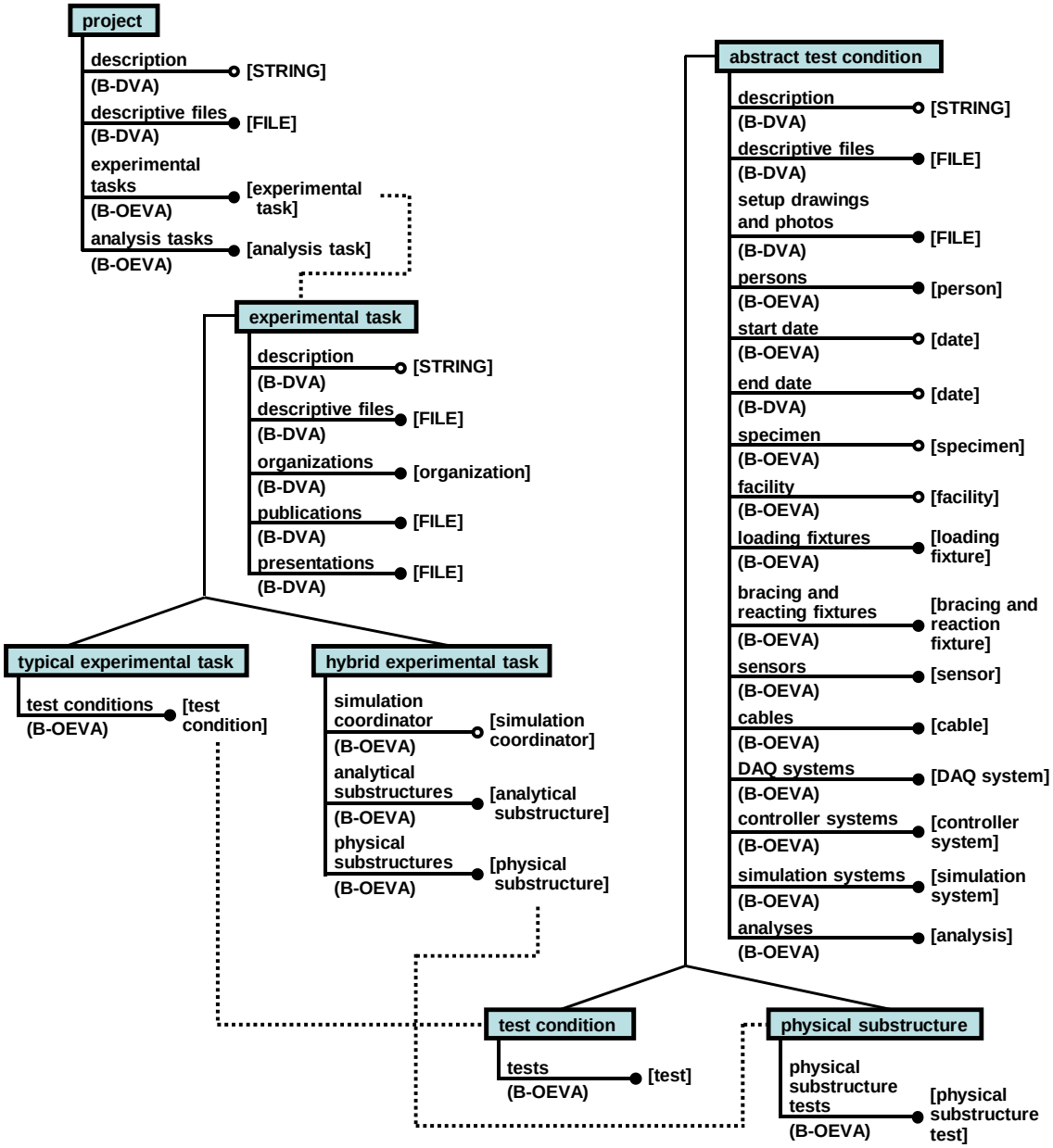


Figure 3.1 Project, Experimental Task, and Test Condition Classes
(Adopted from Lee et al., 2006)

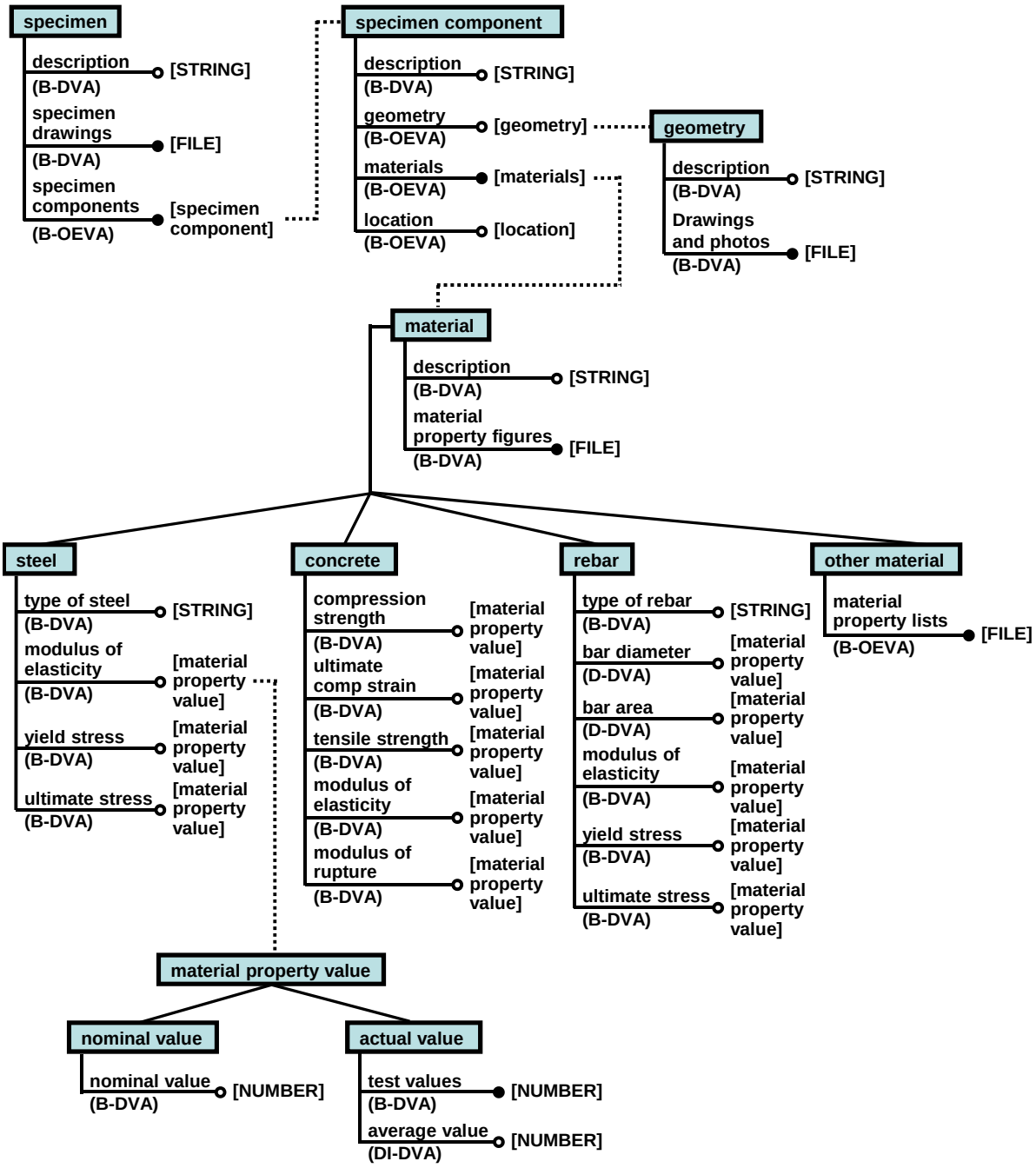


Figure 3.2 Specimen Classes (Adopted from Lee et al., 2006)

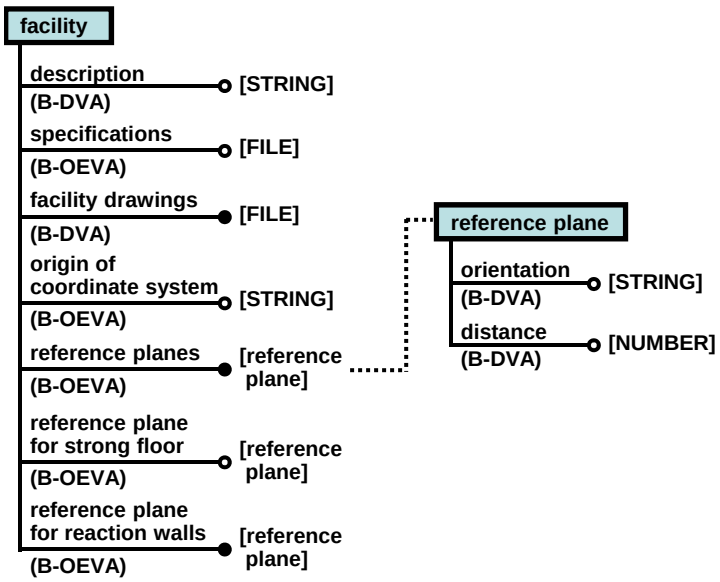


Figure 3.3 Facility Class (Adopted from Lee et al, 2006)

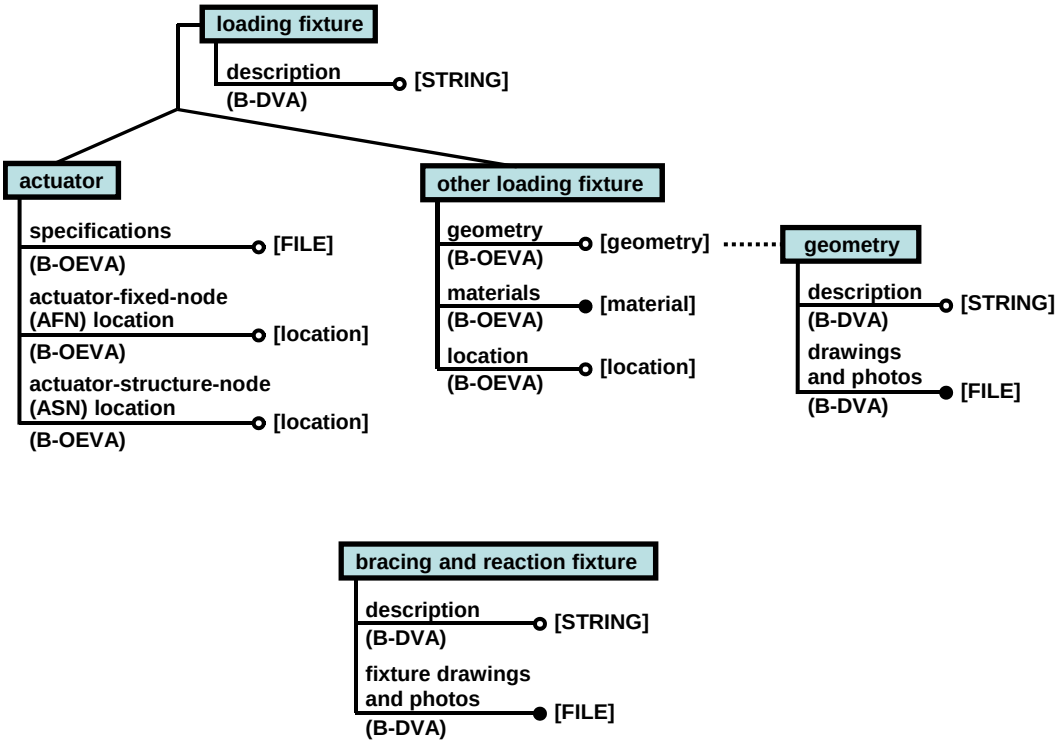


Figure 3.4 Loading Fixture and Bracing and Reaction Fixture Classes
(Adopted from Lee et al., 2006)

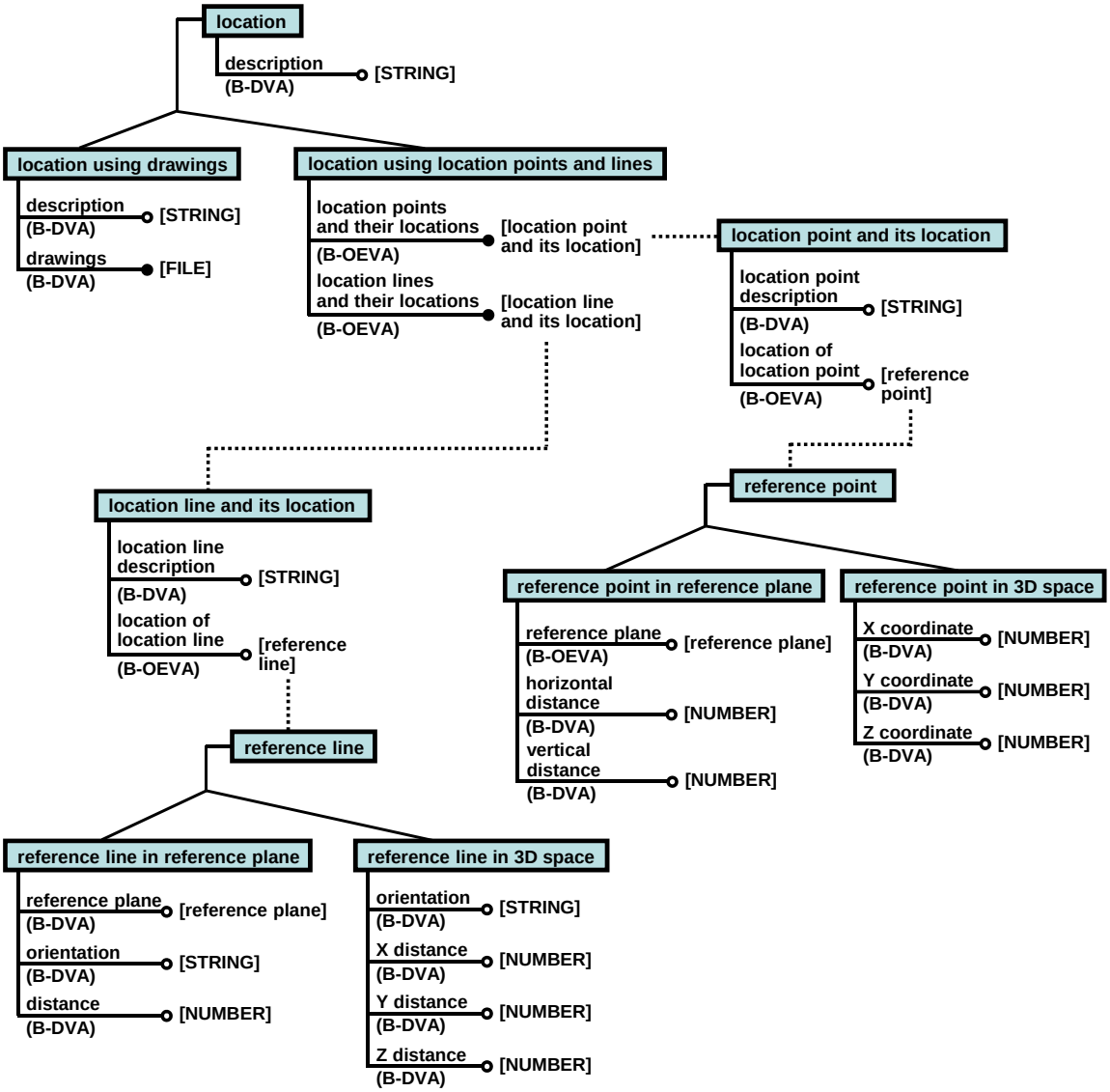


Figure 3.5 Location Class (Adopted from Lee et al., 2006)

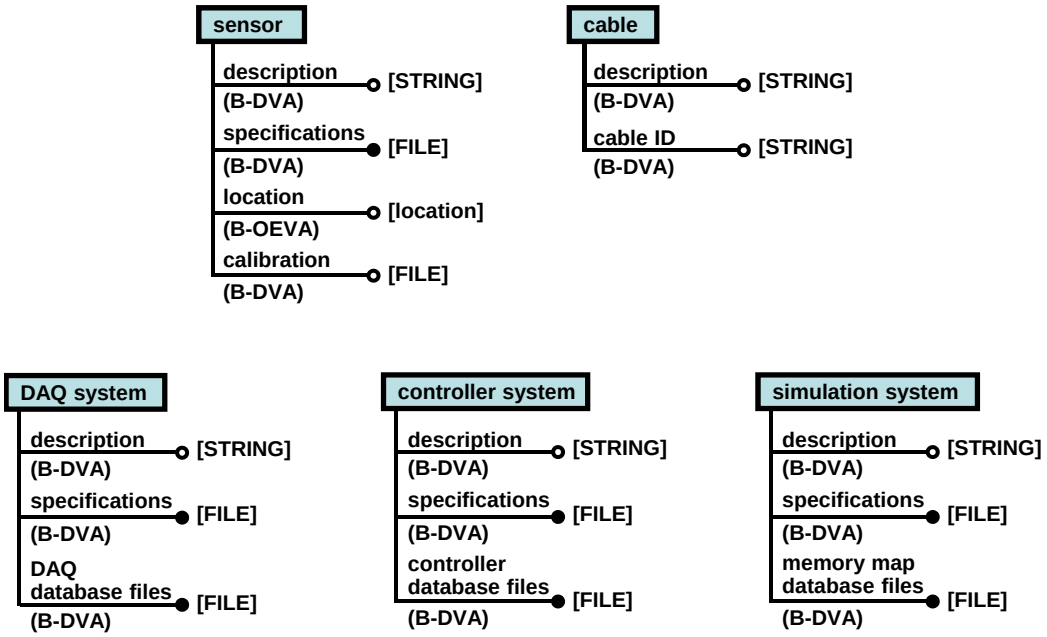


Figure 3.6 Classes for Data Acquisition and Test Control
(Adopted from Lee et al., 2006)

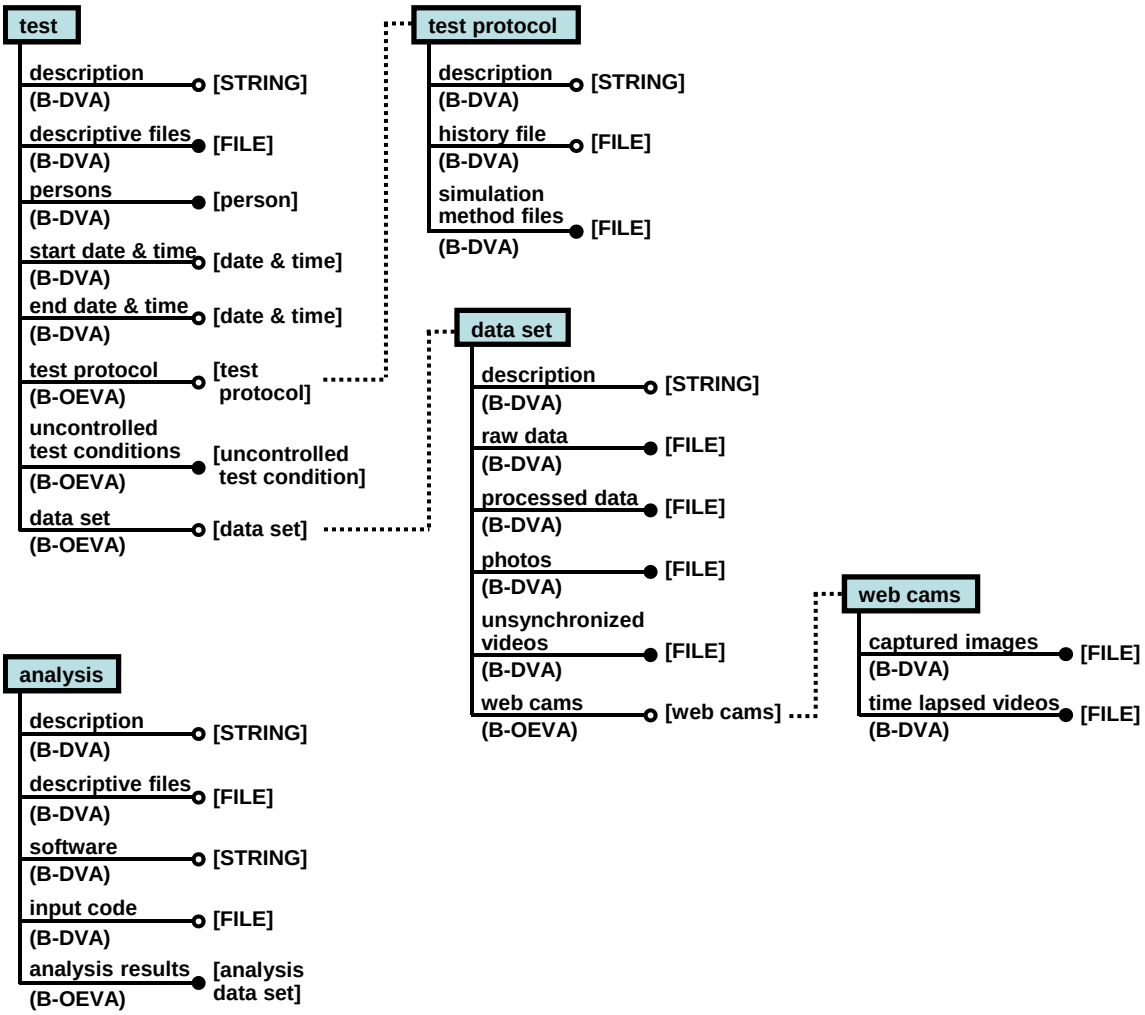


Figure 3.7 Test and Analysis Classes (Adopted from Lee et al., 2006)

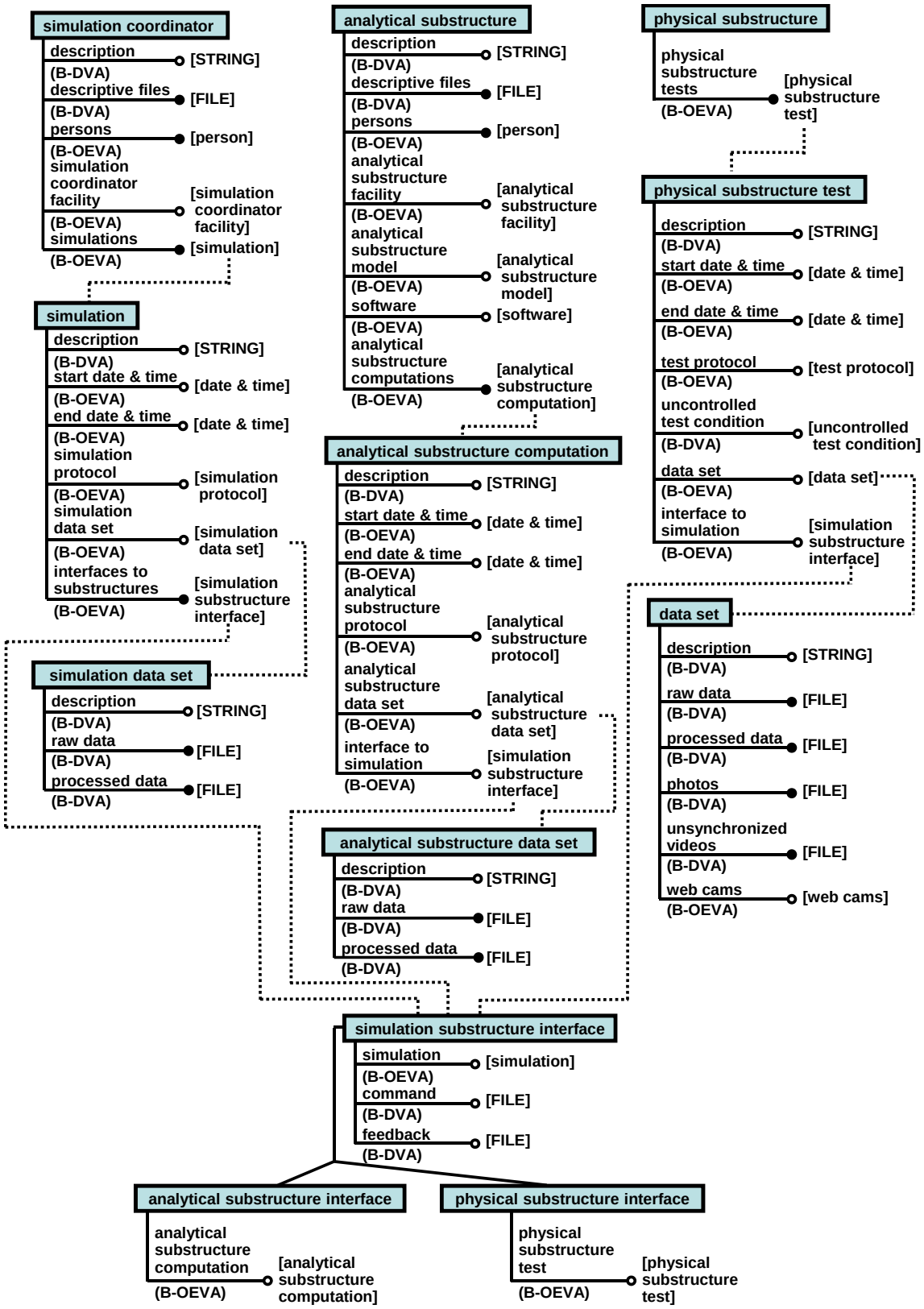


Figure 3.8 Classes of Hybrid Experimental Task (Adopted from Lee et al., 2006)

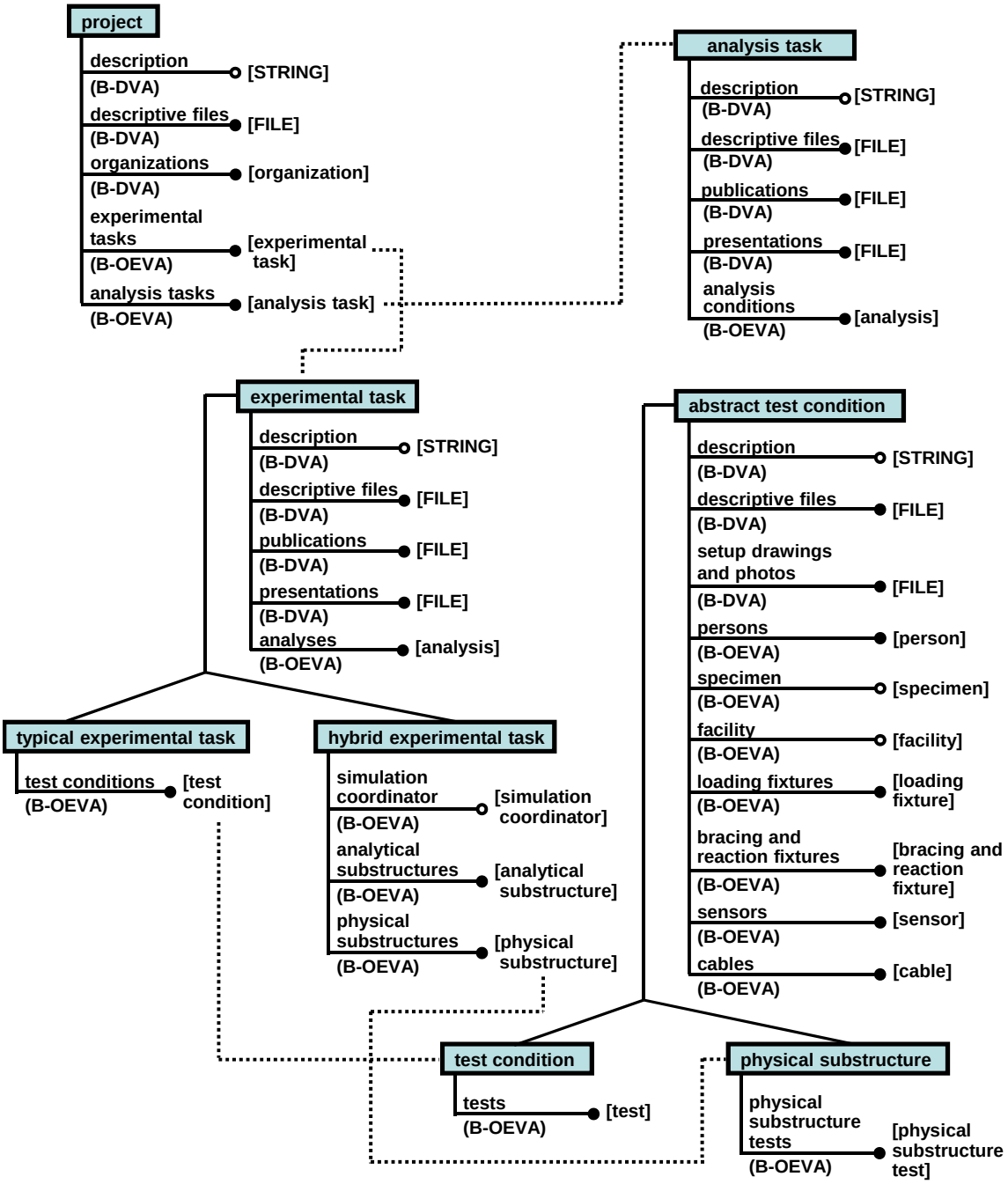


Figure 3.9 Updated Project, Experimental Task, Analysis Task, and Test Condition Classes

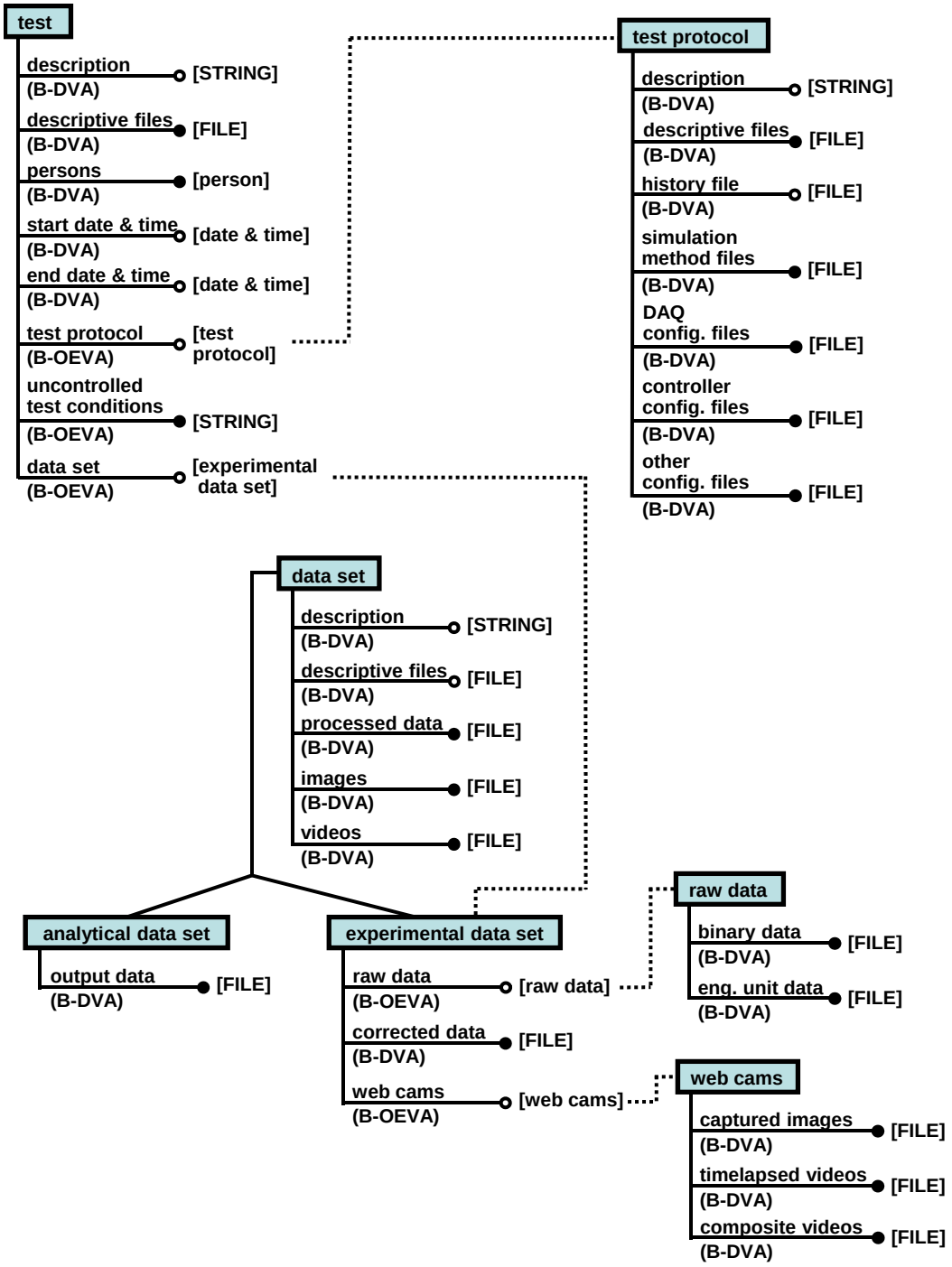


Figure 3.10 Updated Test, Test Protocol, and Data Set Classes

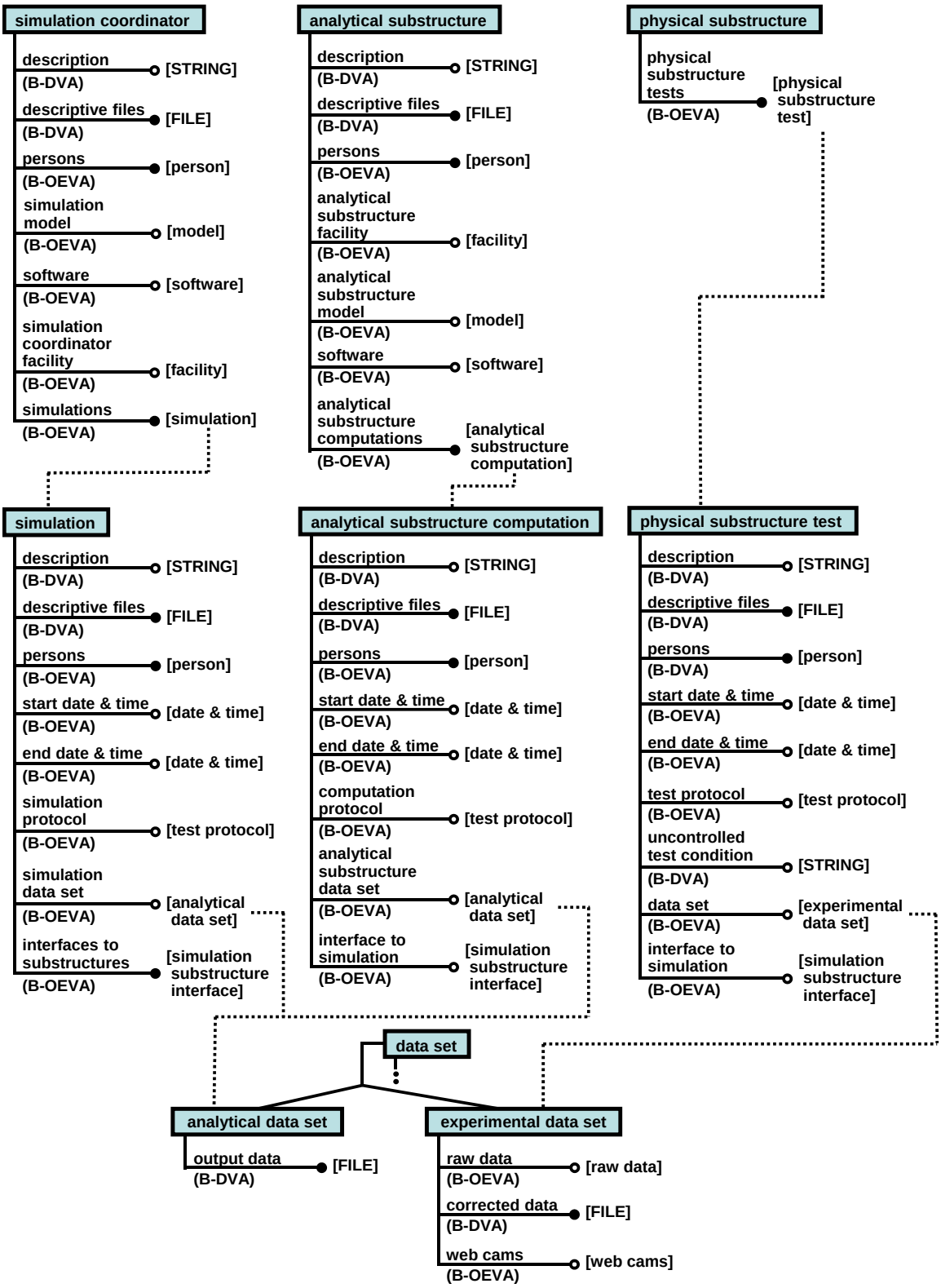


Figure 3.11 Updated Classes of Hybrid Experimental Task

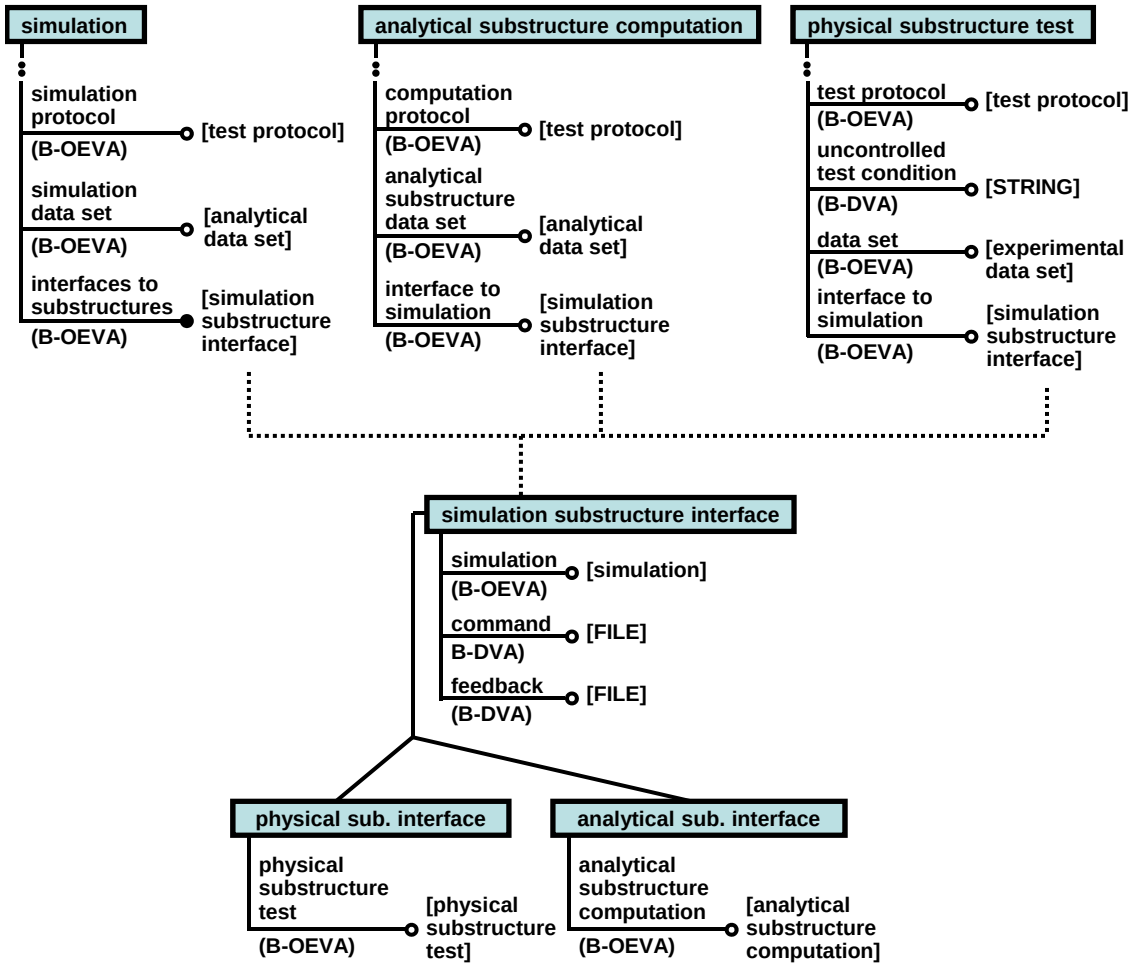


Figure 3.11 Updated Classes of Hybrid Experimental Task (Continued)

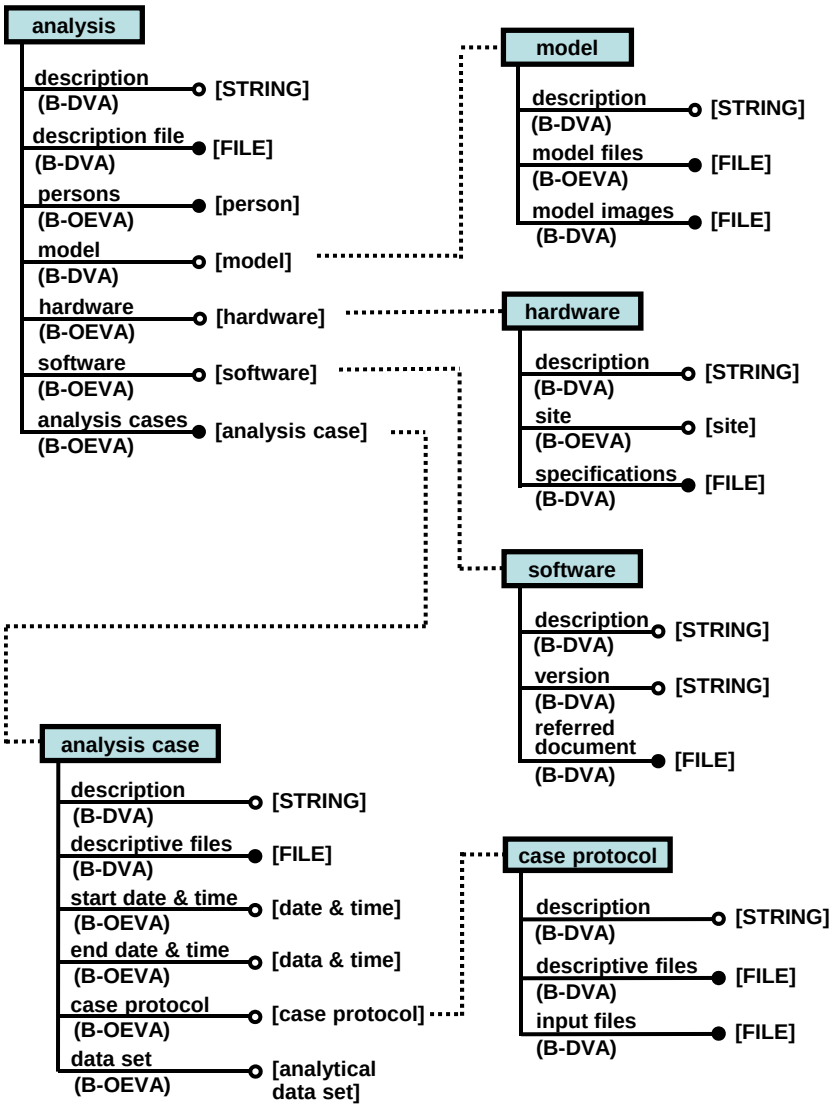


Figure 3.12 Updated Analysis Class and Related Classes

Chapter 4

Lehigh RTMD Metadata Web

4.1. Introduction

This chapter presents the Lehigh RTMD Metadata Web, which is a web application for an implementation of the Lehigh Model. This application was programmed by Marullo (2007) based on the Lehigh Model described by Lee et al. (2006) and on the model described in this thesis.

4.2. Lehigh Model and Lehigh RTMD Metadata Web

A web application was developed at the Real-Time Multi-Directional (RTMD) earthquake simulation facility in the ATLSS Center, and is named the Lehigh RTMD Metadata Web (Marullo, 2007). The Lehigh RTMD Metadata Web is an implementation of the Lehigh Model, which allows users to store, access, retrieve, and search information and data associated with large-scale structural experiments. The relationship between the Lehigh Model and the Lehigh RTMD Metadata Web is described below.

The objects of the classes of the Lehigh Model are represented by the web pages of the Lehigh RTMD Metadata Web. For example, the Test Condition 0 web page shown in Figure 4.1 represents an object of the test condition class shown in Figure 3.9. The attributes of an object and their values are represented in each web page of the Lehigh RTMD Metadata Web. If the value set of an attribute refers to alphanumeric data, such as “STRING”, this value is directly displayed at top of a web page, for example, the

description attribute of the Test Condition 0 web page shown in Figure 4.1. If the value set of an attribute refers to “FILE”, this value is displayed in a rectangular box as a link to access the file, for example, the setup drawings and photos attribute of the Test Condition 0 web page shown in Figure 4.1. If the value set of an attribute refers to another object, this value is presented in a rectangular box as an object link to another web page that corresponds to the class to which the value set refers in the Lehigh Model, for example, the specimen attribute of the Test Condition 0 web page shown in Figure 4.1. A multi-valued attribute is indicated by a plus sign at the end of the rectangular box, for example, the setup drawings and photos attribute as shown in Figure 4.1. A single-valued attribute does not have a plus sign at end after the value is input, for example, the specimen attribute as shown in Figure 4.1.

4.3. Development Tool of Lehigh RTMD Metadata Web

The Lehigh RTMD Metadata Web was developed by Marullo (2007) using PHP and Javascript to produce HTML for web browsers such as Firefox. It interfaces with MySQL, a database system, to store and retrieve data. The Lehigh RTMD Metadata Web reads a user-generated PHP data model schema for a project. This schema provides the hierarchy of the objects from the five main levels of the Lehigh Model to be represented by the Lehigh RTMD Metadata Web, which then presents an interface, as well as web pages as shown in Figure 4.1, for a user to create the objects, to view the objects and to edit or delete the objects as described in the following section 4.4. A PHP data model configuration defines created object names and lists direct child objects and shared objects for interacting with the MySQL database. The MySQL database

contains a generic template table which allows any type of object to be instantiated. This new row of data contains the object data along with a reference to its unique parent ID. Another template table exists to maintain one-to-many (1-M) and many-to-many (N-M) object relationships, called shared objects in the Lehigh RTMD Metadata Web. Figure 4.2 shows the interaction between the PHP data model configuration and MySQL database to enable the web application to view objects and related data. This implementation allows the data model to be easily changed without having to modify the database structure.

4.4. Brief Guide to Lehigh RTMD Metadata Web

The Lehigh RTMD Metadata Web has security to protect experimental resources, as shown in Figure 4.3; it requires users to login. The administration web page shown in Figure 4.4 allows users to request membership to a specific project to view or update the data. All of the projects in the Lehigh RTMD Metadata Web database are listed in the Projects web page shown in Figure 4.5. If the project name is displayed in black, the user has authority to access that project; if the project name is displayed in gray, the user is not permitted to access that project. Users are permitted to create their own projects by clicking on the “Add Project” button under the listed projects.

A project, called the Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems project, is selected as an example to present the Lehigh RTMD Metadata Web. The objects related to the five main levels of the Lehigh Model for the project are shown in Figures 4.6, 4.7, 4.1, 4.8, and 4.9. Figure 4.6 shows the Self-Centering Damage-Free

Seismic-Resistant Steel Frame System project web page as an object of the project class at the project class level. Figure 4.7 shows the Develop Energy Dissipation Elements Appropriate for SC-MRF and SC-CBF Systems web page as an object of the typical experimental task class at the experimental task class level. Figure 4.1 shows the Test Condition 0 web page as an object of the test condition class at the test condition class level. Figure 4.8 shows the Test 0A web page as an object of the test class at the test class level. Finally, Figure 4.9 shows the Test 0A data set web page as an object of the data set class at the data set class level. A lower level object is accessed by clicking the object link in the rectangular box that corresponds to the attribute representing the lower level object; a higher level object can be reached by clicking on the back arrow button at bottom of the web page.

The information and data for each object is shown on each web page in boxes that correspond to the attributes of the object. When the value set of an attribute refers to “STRING” or “NUMBER”, this value can be input or modified in the text area as shown in Figure 4.10 by clicking on the “Edit” button on the bottom of a web page as shown in Figure 4.1. When the value set of an attributes refers to “FILE”, a file can be uploaded via the web page as shown in Figure 4.11 by clicking on the plus sign button at the right end of an attribute box on a web page as shown in Figure 4.1. When the value set of an attribute refers to another object, an object link can be created by clicking on the plus sign button at the right end of an attribute box on a web page as shown in Figure 4.1. Figure 4.12 and Figure 4.13 illustrate how to create an object link to a shared object and a non-shared object, respectively. A shared object is introduced in the Lehigh RTMD

Metadata Web application to allow an object to be shared between other projects, because the same object may be used in different projects, for instance, the actuator in the Test Condition 0 web page shown in Figure 4.1. A specific actuator at the RTMD earthquake simulation facility can be used for many experiments in the facility. As shown in Figure 4.12, an object link for the actuator can be created by selecting an existing, shared object of NEES Actuators or by adding a new actuator object which permits this new object to be shared with other projects. Figure 4.13 shows the web page for creating a non-shared object which is a unique object in a project, for instance, the tests in the test condition 0 web page shown in Figure 4.1, because each test represents a unique experiment. In order to present each web page with clarity, all file and object links are hidden inside the rectangular boxes. When the text in the rectangular box is displayed in bold type, it means that there are files or object links hidden in the rectangular box. These files or object links are displayed by clicking on the triangle sign at the left side of the rectangular box, as shown in Figure 4.1.

4.5. Summary

The Lehigh RTMD Metadata Web (Marullo, 2007) was developed to implement the Lehigh Model, and to enable the information and data associated with large-scale structural experiments to be stored, accessed, and searched. The web pages of the Lehigh RTMD Metadata Web represent objects of the classes of the Lehigh Model; the rectangular boxes on the web pages represent the attributes of an object. PHP and Javascript code, interfacing with MySQL to store and retrieve data, were used to develop this web application.

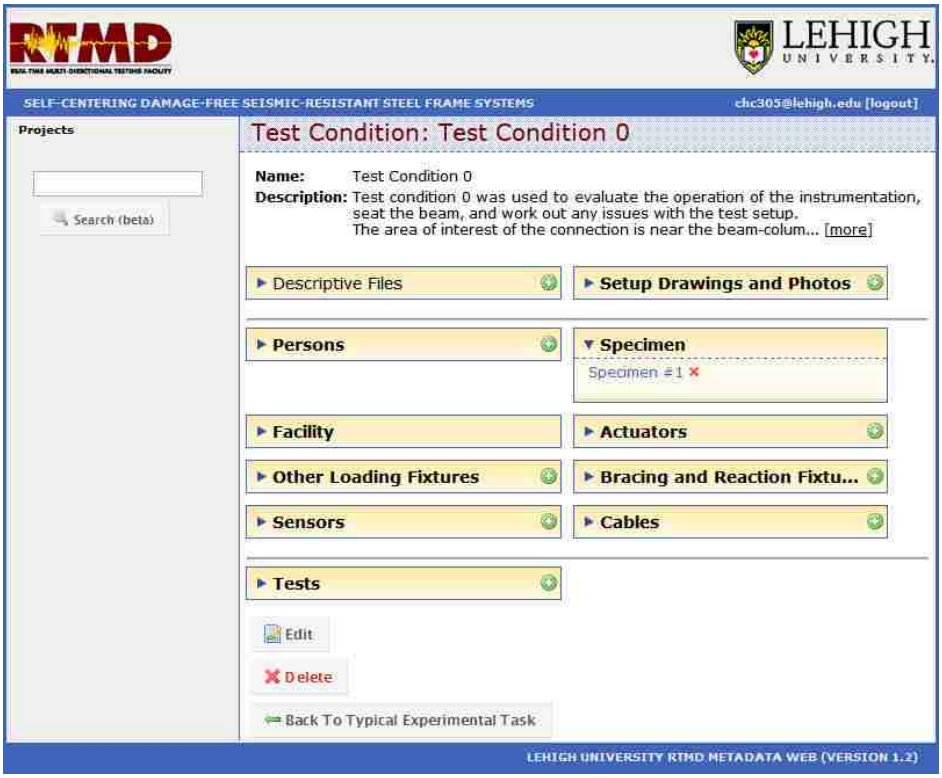


Figure 4.1 Test Condition 0 Web Page of Lehigh RTMD Metadata Web

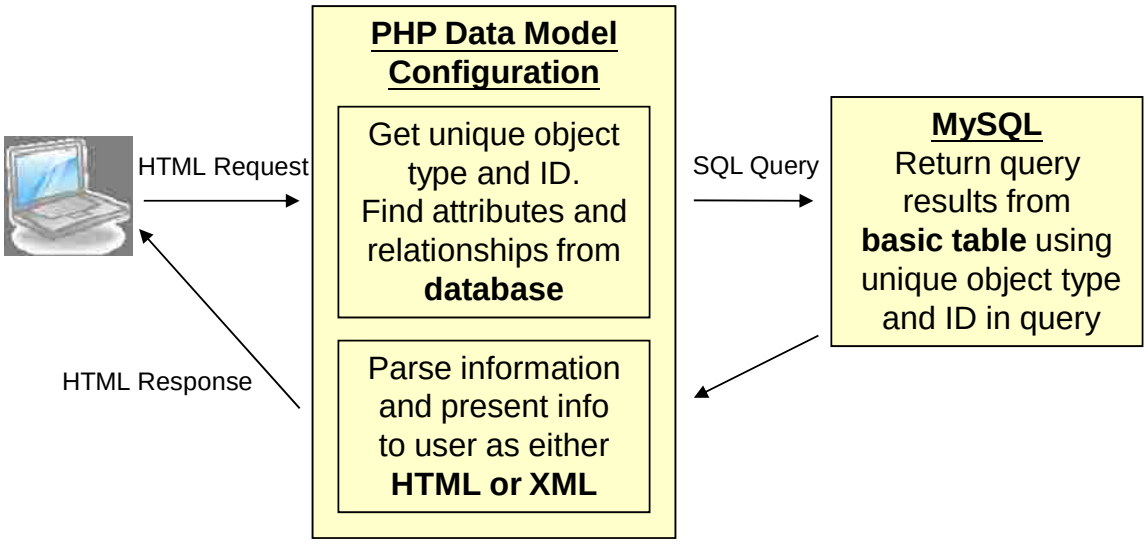


Figure 4.2 Interaction between PHP Data Model Configuration and MySQL

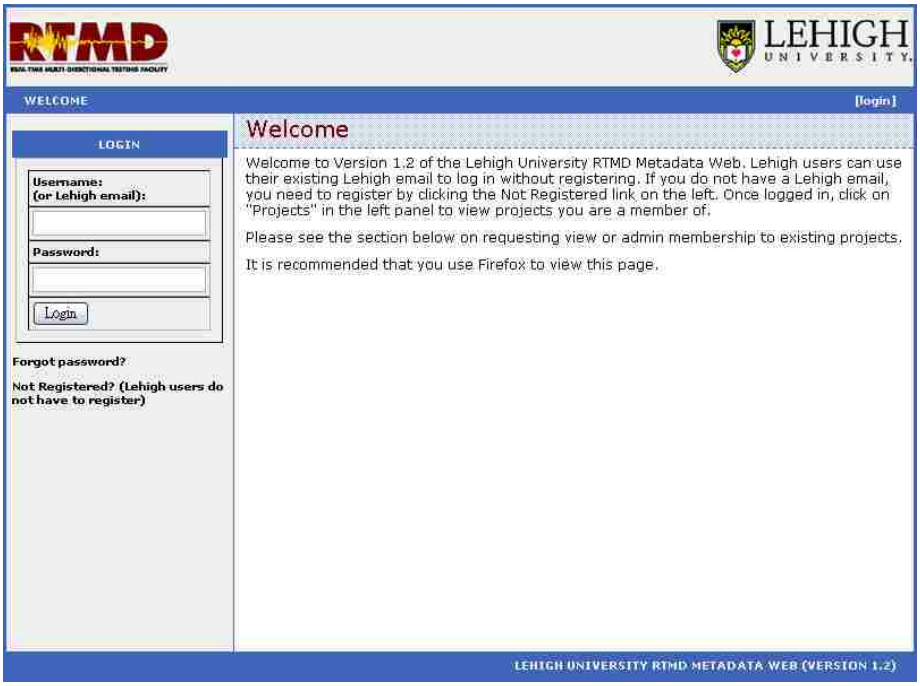


Figure 4.3 Login Web Page of Lehigh RTMD Metadata Web

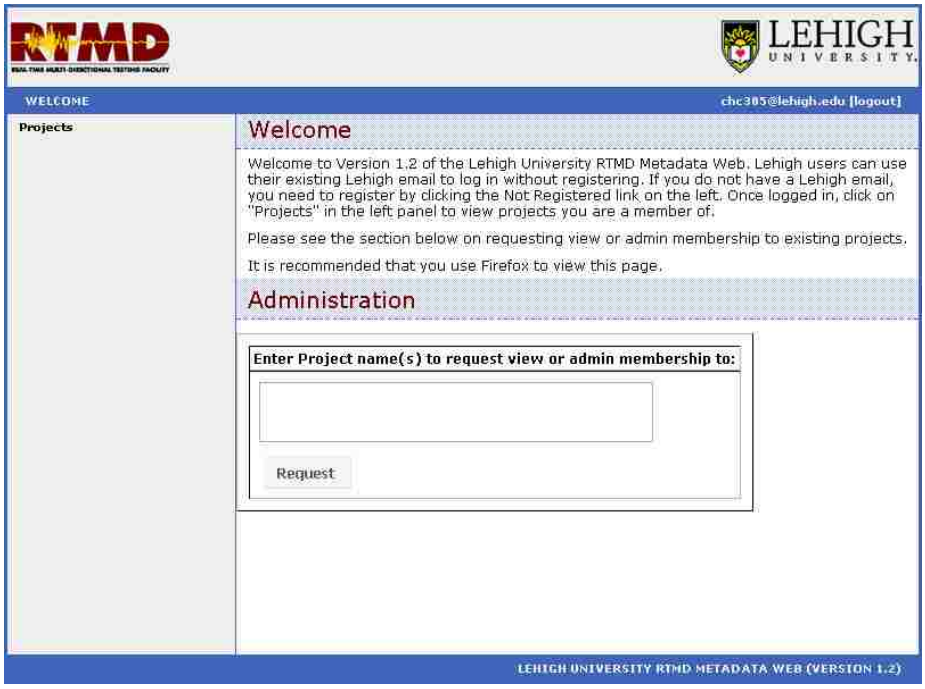


Figure 4.4 Administration Web Page of Lehigh RTMD Metadata Web

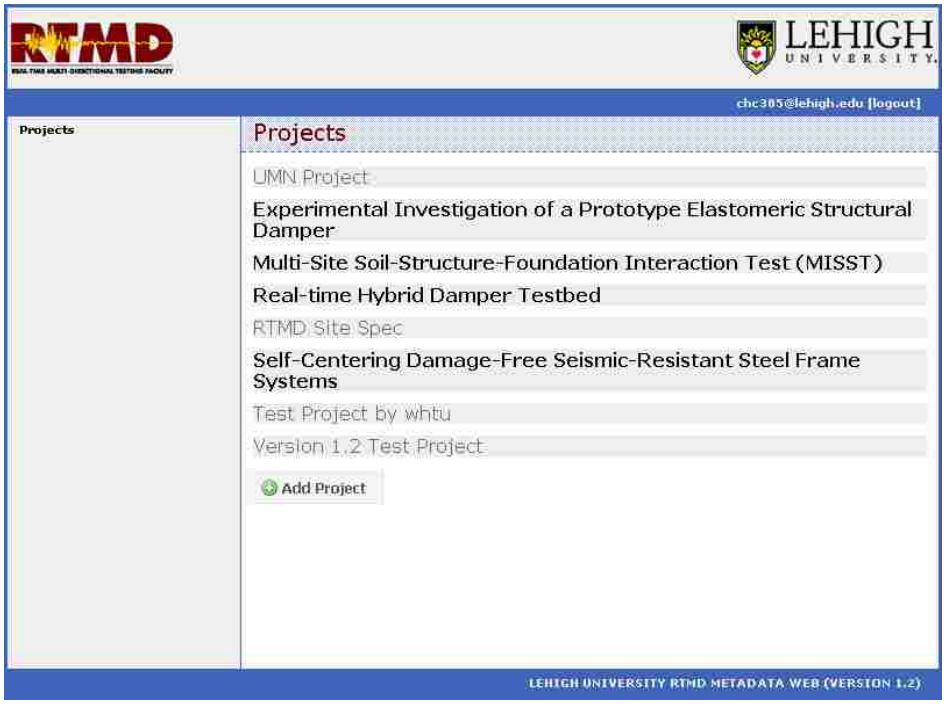


Figure 4.5 Projects Web Page of Lehigh RTMD Metadata Web

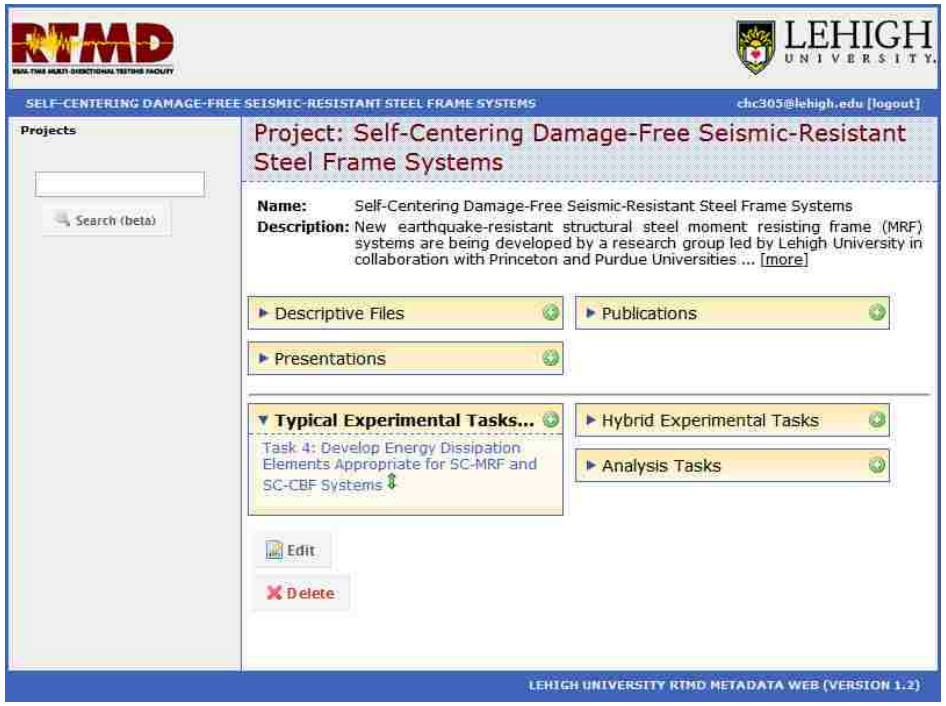


Figure 4.6 Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems Web Page of Lehigh RTMD Metadata Web

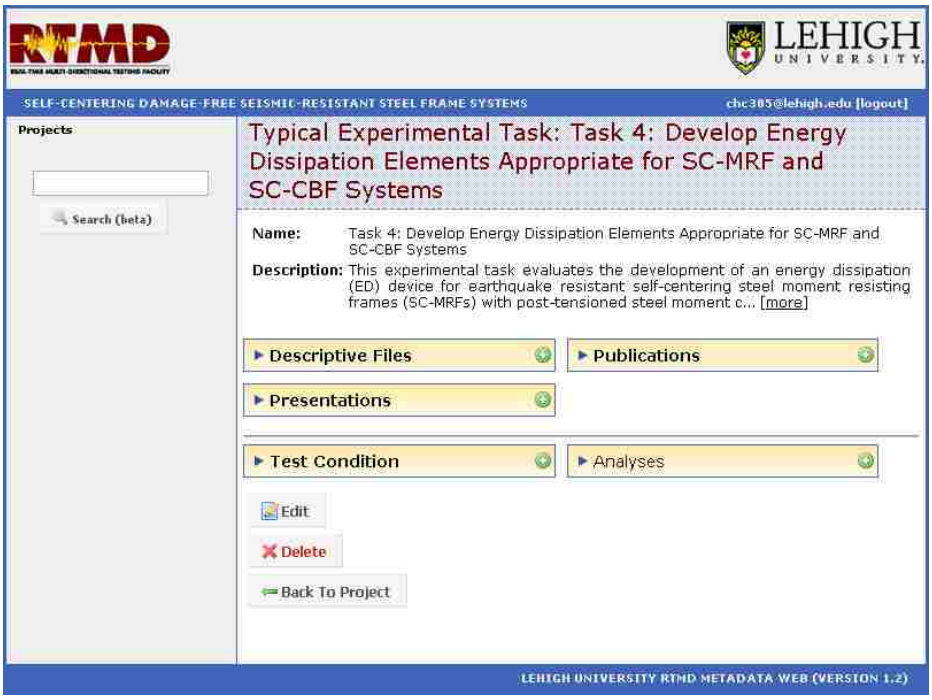


Figure 4.7 Task 4: Develop Energy Dissipation Elements Appropriate for SC-MRF and SC-CBF System Web Page of Lehigh RTMD Metadata Web

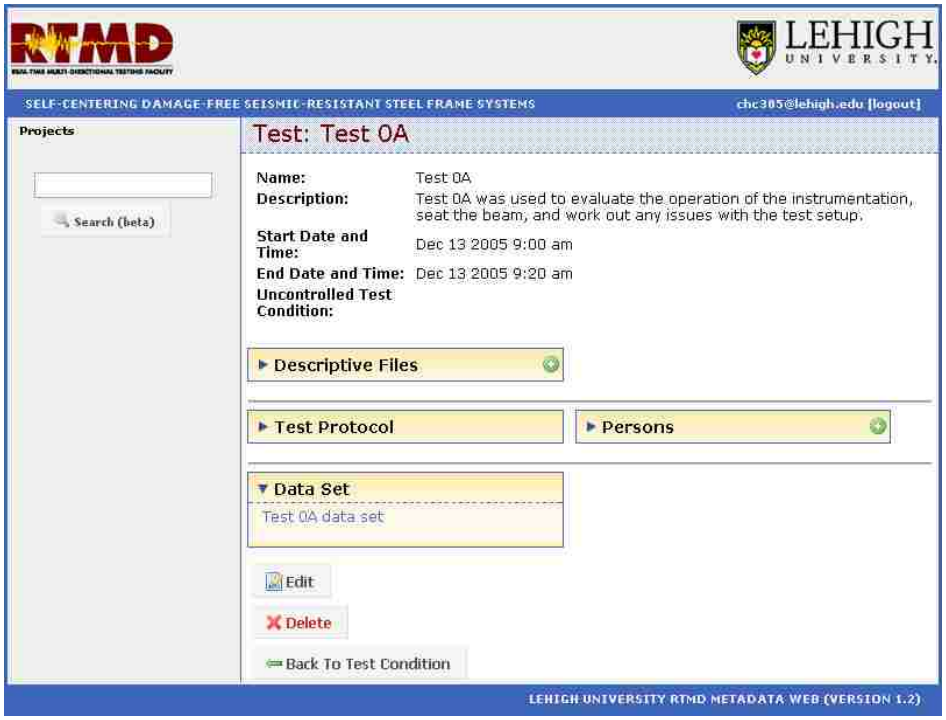


Figure 4.8 Test 0A Web Page of Lehigh RTMD Metadata Web

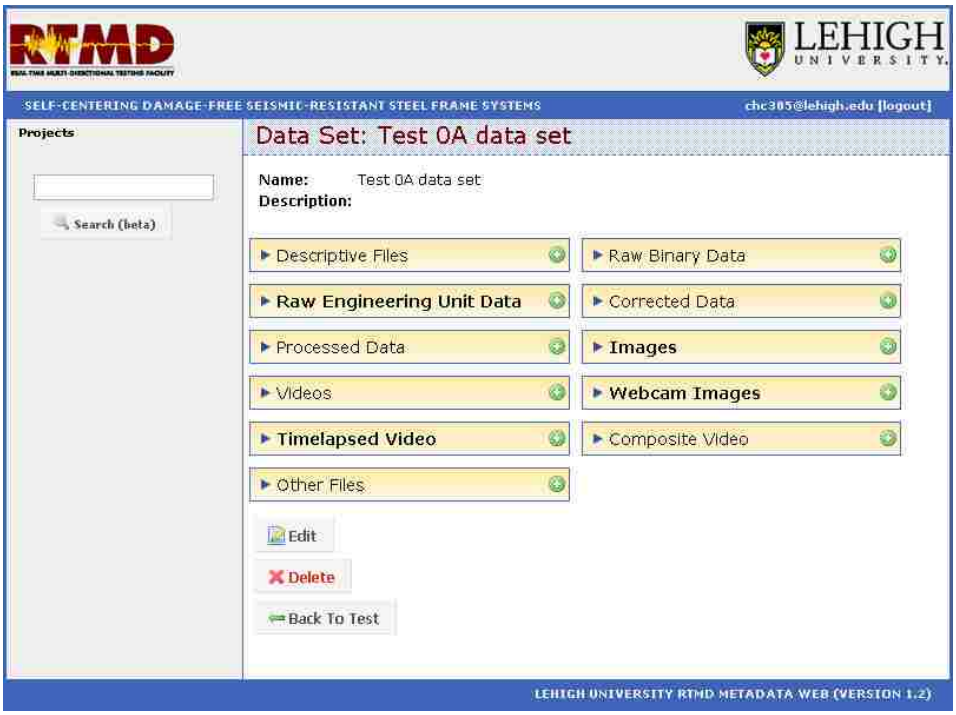


Figure 4.9 Test 0A Data Set Web Page of Lehigh RTMD Metadata Web

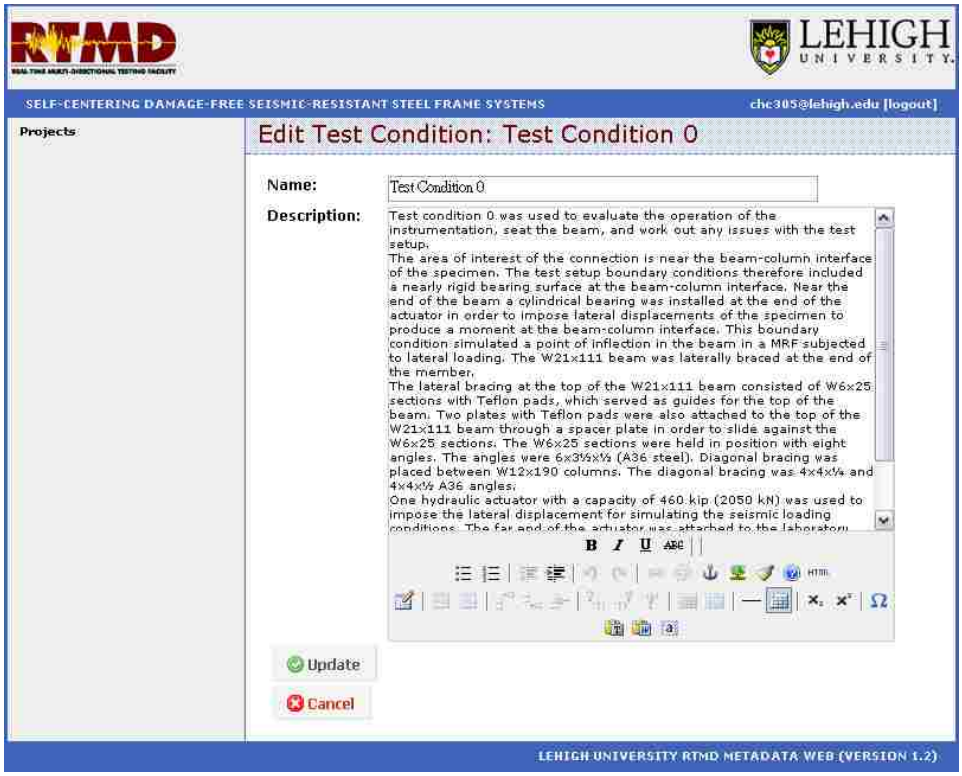


Figure 4.10 Example of Editing Description

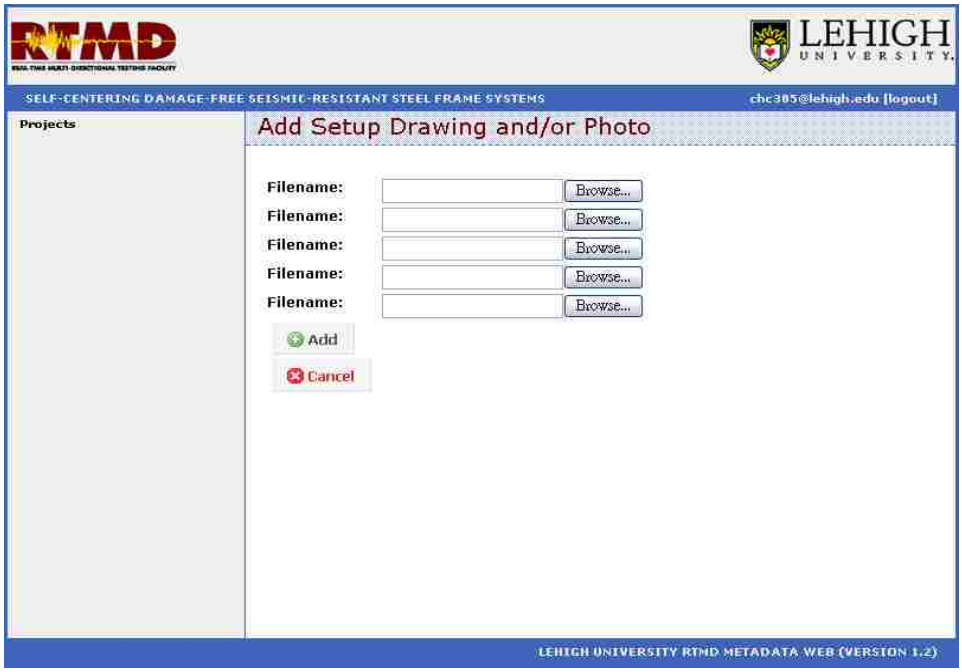


Figure 4.11 Example of Uploading Files

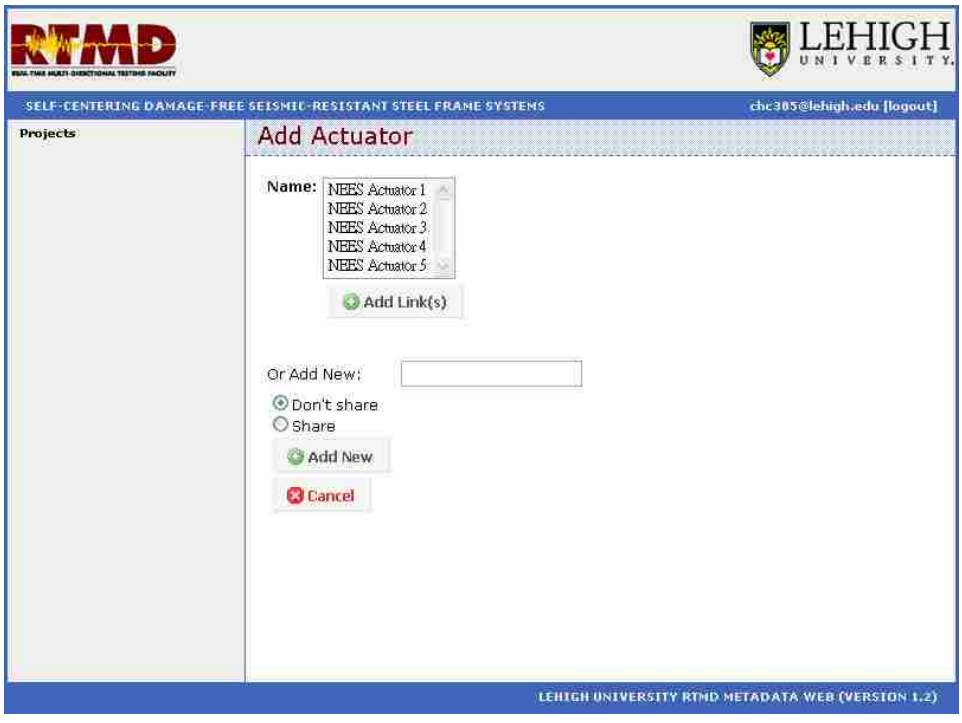


Figure 4.12 Example of Creating a Shared Object

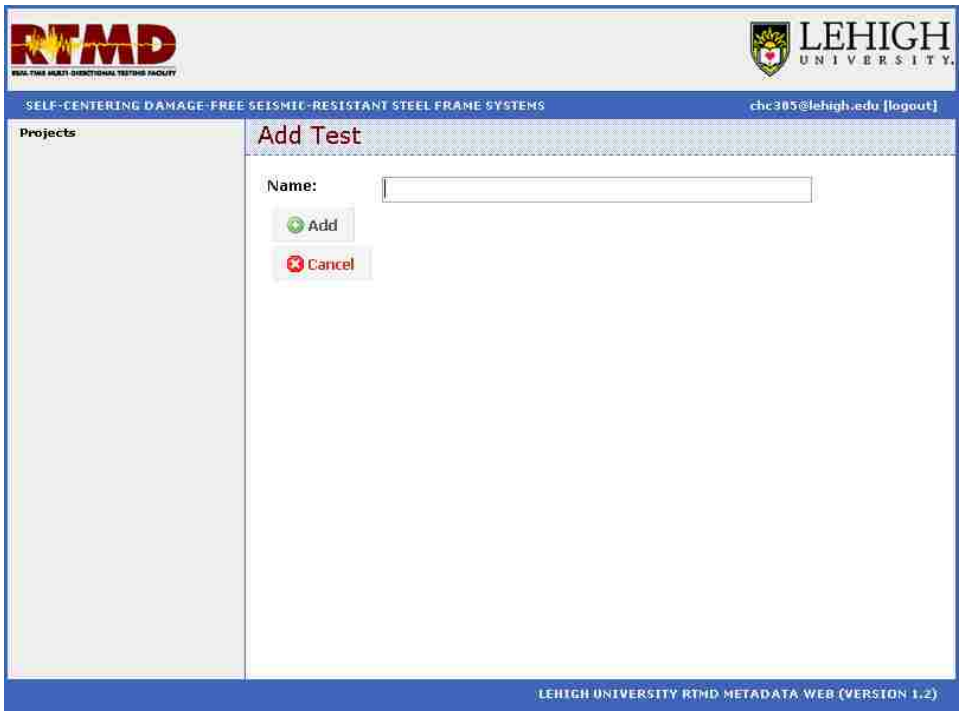


Figure 4.13 Example of Creating a Non-shared Object

Chapter 5

Example of Lehigh RTMD Metadata Web Applied to Typical Experiment

5.1. Introduction

An experimental task of the Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems project is used as an example of applying the Lehigh RTMD Metadata Web to a typical experiment. The information and data associated with this experiment are organized using the Lehigh RTMD Metadata Web. The information and data are presented in the five main levels of the Lehigh Model (the project class level, the experimental task class level, the test condition class level, the test class level, and the data set class level).

5.2. Background of Project

The purpose of the project, Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems, is to investigate steel moment resisting frames (MRFs) with posttensioned steel moment connections (PT connections) (Ricles et al., 2001) under earthquake loading. One of the experimental tasks of the project, which included a number of structural tests conducted at the RTMD earthquake simulation facility at the ATLSS Center, is to evaluate energy dissipation (ED) devices for earthquake resistant self-centering steel moment resisting frames (SC-MRFs) with PT connections (Wolski, 2006). The information and data associated with this experimental task are used to present the application of the Lehigh RTMD Metadata Web to a typical experiment.

The basic experimental setup is displayed in Figure 5.1. An exterior PT steel MRF connection with a bottom flange friction device (BFFD) (Wolski, 2006) from the prototype structure shown in Figure 5.1(a) was investigated. The prototype beam section in this experimental task is an A572 Grade 50 W36x300 section. This section was scaled by 3/5 resulting in an A572 Grade 50 W21x111 section in the test specimen shown in Figure 5.1(b). The beam in the test specimen is oriented to the vertical position for convenience in the lab. The connection was designed to replicate the elongation of the strands in the prototype structure, where the elongation of each PT strand is approximately the same. In order to accomplish this, the strands are concentrated at the centroid of the beam section as shown in Figure 5.1(b). Figure 5.1(c) shows a photo of the experimental setup in the RTMD earthquake simulation facility.

5.3. Information and Data in Lehigh RTMD Metadata Web

The information and data associated with the selected experimental task has been organized using the Lehigh RTMD Metadata Web. Only selected web pages and related files are presented for this application example. The information and data are presented in the five main levels of the Lehigh Model, which are the project class level, the experimental task class level, the test condition class level, the test class level, and the data set class level.

5.3.1. Project Class Level and Experimental Task Class Levels

The fundamental information on the project can be found in the Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems Project web page shown in Figure

5.2, which represents an object of the project class of the Lehigh Model. The description describes the overall project and its research objectives. Files for related publications and presentations associated with this project are contained in the publications and presentations attributes. The object link in the typical experimental task attribute provides access to the Task 4: Develop Energy Dissipation Elements Appropriate for SC-MRF and SC-CBF Systems web page shown in Figure 5.3, which represents an object of the typical experimental task class of the Lehigh Model.

A description of this experimental task is shown in Figure 5.3. The Test Matrix in the descriptive files attribute provides the configuration of the tests for this experimental task. The BFFD Status Report 1, the thesis by Wolski (2006), and the 4ICEE conference paper shown in Figure 5.4 (a) through (c), respectively, are contained in the publications attribute. The presentation by Wolski (2006) is available from the presentation attribute. A number of object links in the test condition attribute provide access to each test condition used in this experimental task.

5.3.2. Test Condition Class Level

As defined in the Lehigh Model, a typical experimental setup consists of several major components, which are the specimen, facility, sensors, loading fixtures, bracing and reaction fixtures, and cables. Information on these components for a typical experimental setup can be found in corresponding web pages, such as the Test Condition 5 web page shown in Figure 5.5. This web page represents an object of the test condition class of the Lehigh Model. The Test Condition 5 web page is one of nine

experimental setups used in this experimental task as shown in Figure 5.3. The other test conditions are accessed from the object links in the test conditions attribute shown in Figure 5.3.

A description of this experimental setup is given in the Test Condition 5 web page shown in Figure 5.5. An AutoCAD file, named setup drawings, can be accessed from the setup drawings and photos attribute to provide an illustration of the experimental setup. The information about the related specimen, facility, loading fixtures, bracing and reaction fixtures, sensors, and cables can be found in the web pages accessed from the object links in the corresponding attributes as shown in Figure 5.5. A number of tests performed using this experimental setup can be accessed from the object links in the tests attributes shown in Figure 5.5.

Specimen # 2 is the test specimen used for this experimental setup and its detailed information is represented on the Specimen # 2 web page shown in Figure 5.6. This web page represents an object of the specimen class of the Lehigh Model. The description contains information about Specimen # 2. The AutoCAD file from the specimen drawings and photos attribute provides an illustration of the specimen as shown in Figure 5.7. The information about specimen components are found in the web pages accessed from the object links in the specimen components attribute. The BFFD (Fillet Weld) web page shown in Figure 5.8 represents one of specimen components used in Specimen # 2. The detailed information about this component is represented in the description, location, geometry, and material attributes. The Location of BFFD web

page shown in Figure 5.9 provides access to geometric location data for the BFFD, which is in Tab-E1 of the setup drawing file in the drawings and photos attribute as shown in Figure 5.7. The Geometry of BFFD web page shown in Figure 5.10 provides access to geometry information for the BFFD, which is in Tab-S1 of the setup drawing file as shown in Figure 5.11. Each specimen component has its own material information as shown in the BFFD (Fillet Weld) web page. For instance, the Material of Slot Pate web page shown in Figure 5.12 represents the steel material information for this specimen component with a steel type, elastic modulus, yield stress, ultimate stress, and material property files. Figure 5.13 shows the yield stress with the nominal value and the average material test value. Information on materials which are not standard steel, concrete, or reinforcing bars, are represented using a web page for other material, for example, the Material of Friction Plate web page shown in Figure 5.14.

The Real-Time Multi-Directional (RTMD) Facility web page shown in Figure 5.15 represents an object of the facility class of the Lehigh Model. The general information about this facility used for this experimental setup is provided in the description. The specification files in the specifications attribute provide more detailed information about the equipment used in the RTMD earthquake simulation facility as shown in Figure 5.16.

NEES Actuator 2 is part of loading fixtures used in the experimental setup. Information about this actuator can be found on the NEES Actuator 2 web page shown in Figure 5.17, which represents an object of the actuator class of the Lehigh Model. The descriptive

files, specifications, and drawings and photos attributes provide detailed information about this actuator, as shown in Figure 5.18.

The bracing and reaction fixture used in the experimental setup is represented in the Bracing fixture for specimen (adjusted) web page shown in Figure 5.19, which represents an objection of the bracing and reaction fixture class of the Lehigh Model. The description provides information about the components of this bracing and reaction fixture. An illustration of this bracing and reaction fixture is provided by the AutoCAD file in the fixture drawings and photos attributes as shown in Figure 5.7.

The LVDT-3 web page shown in Figure 5.20 represents an object of the sensor class of the Lehigh Model. Figure 5.21 shows the calibration and specification files for this sensor. These files can be accessed from the calibration and specifications attributes shown in Figure 5.20. The object link in the location using drawings and photos attributes provides access to the Location of LVDT-3 web page shown in Figure 5.22 which indicates the location information using the AutoCAD file in the drawings and photos attribute as shown in Figure 5.23.

Figure 5.24 shows the Cables web page, which represents an object of the cable class of the Lehigh Model. The information about the cables was not recorded when the experiment was performed, so all of the cables are described on one web page with the types and number of cables that were used in the experimental setup.

5.3.3. Test Class Level

As defined in the Lehigh Model, a test condition can include more than one test. As shown on the Test Condition 5 web page (Figure 5.5), three tests were performed using this experimental setup. The information about these tests can be found on web pages, such as the Test 5B web page shown in Figure 5.25. This web page represents an object of the test class of the Lehigh Model. This web page includes a brief description about Test 5B. The information on the loading protocol for this test is represented on the Test protocol # 14 web page shown in Figure 5.26, which can be accessed from the object link in the test protocol attribute shown in Figure 5.25. The description describes the loading method and important parameters of this loading protocol. The history file attribute provide information about the loading history used for this test. Only the simulation and DAQ configuration files are available for this test and these files are accessed by the simulation method files and DAQ config files attributes shown in Figure 5.26. The results of this test can be accessed from the object link in the data set attribute shown in Figure 5.25.

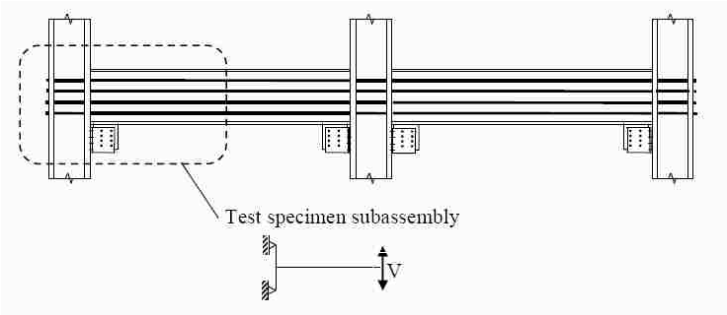
5.3.4. Data Set Class Level

The test results for Test 5B are represented on the Test 5B data set web page shown in Figure 5.27, which represents an object of the experimental data set class of the Lehigh Model. The description and descriptive files contain information about the resulting data. The data is accessed from the raw data engineering unit attribute, the corrected data attribute, and the processed data attribute. Files corresponding to these attributes can be retrieved using links on this web page. The Test 5B data set web page also

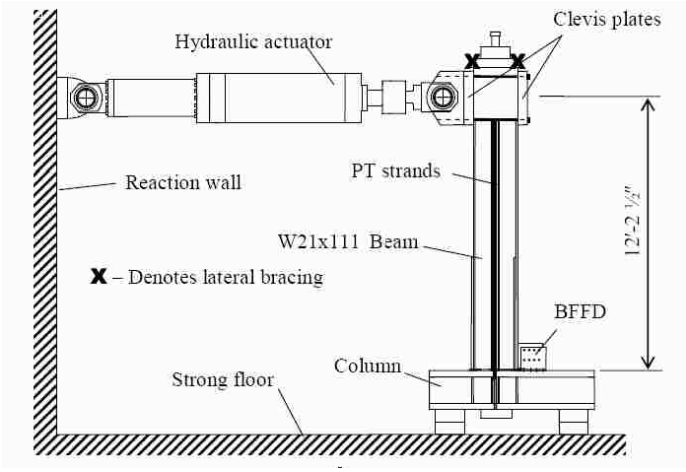
provides access to images, videos, webcam images and webcam videos (as well as timelapse videos and composite videos) for Test 5B.

5.4. Summary

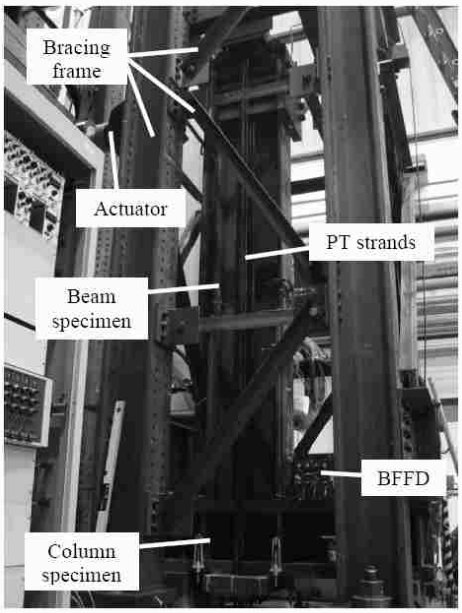
A typical experimental task from the Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems project is presented as an example of applying the Lehigh RTMD Metadata Web to a typical experiment. A brief introduction of the experimental task was given. The application of the Lehigh RTMD Metadata Web was presented in figures that show the information and data related to the experiment. Information about the project and the typical experimental task is represented on web pages at the project class level and the experimental task class level. The configuration of a typical experimental setup is represented on the web pages at the test condition class level, with detailed information about the specimen, facility, actuators, loading fixtures, bracing and reaction fixtures, sensors, and cables. The loading protocol for the tests is represented on the web page at the test class level. Experimental data, such as raw data, corrected data, processed data, and images and videos from cameras and webcams are represented on web pages at the data set class level.



a. Prototype Structure



b. Test Setup



c. Photo of Test Setup

Figure 5.1 Experiments on PT Connection with BFFD (Adopted from Wolski, 2006)

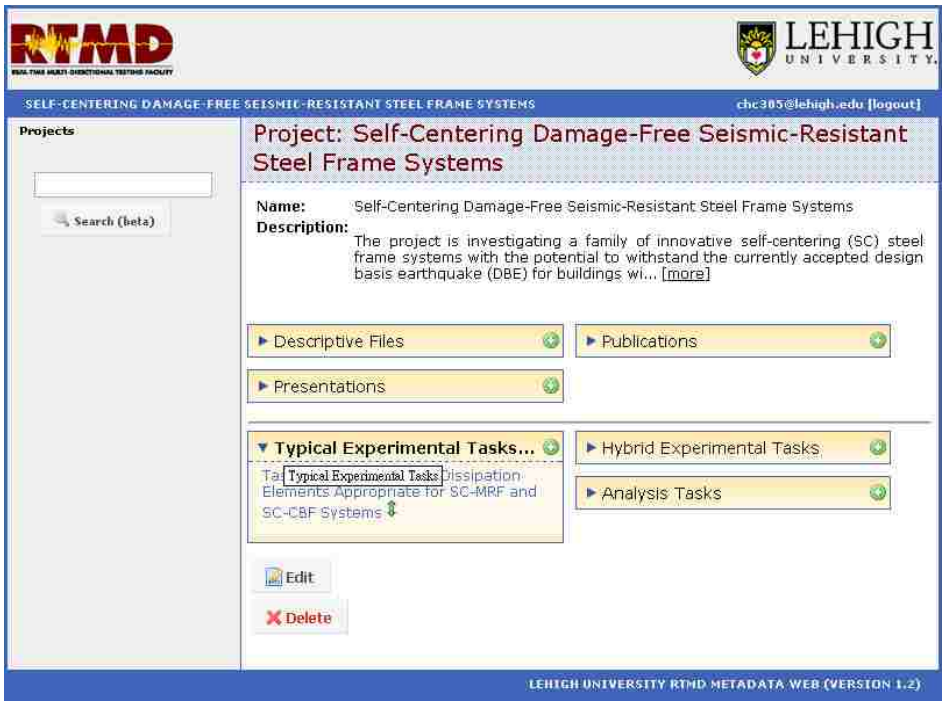


Figure 5.2 Self-Centering Damage Free Seismic-Resistant Steel Frame Systems Project Web Page

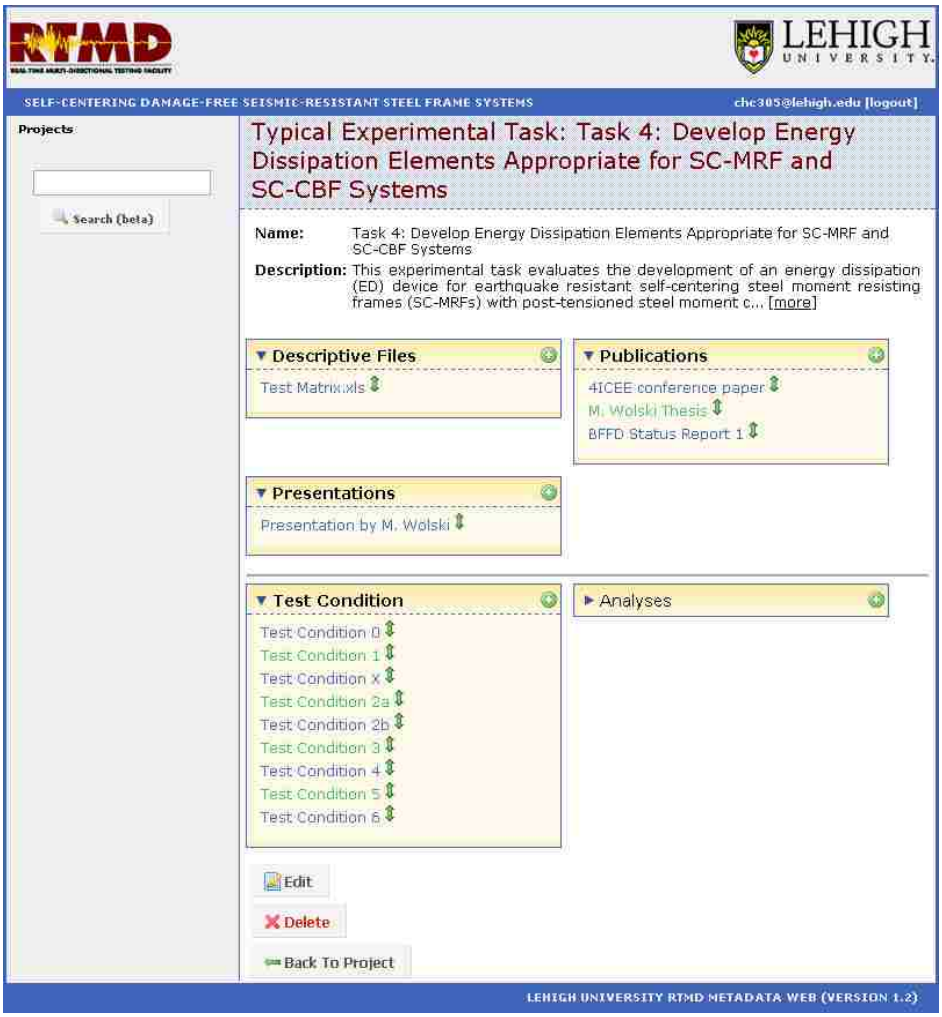
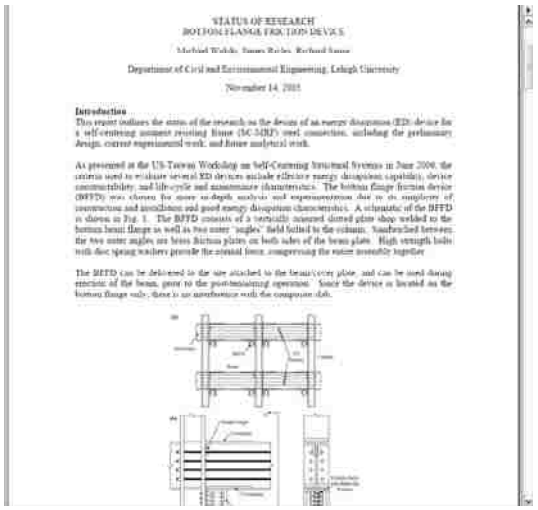


Figure 5.3 Task 4: Develop Energy Dissipation Elements Appropriate for SC-MRF and SC-CBF Systems Web Page



STATUS OF RESEARCH
BOTTOM FLANGE FRICTION DEVICE

Michael Wolski, James Ricles, Richard Sause

Department of Civil and Environmental Engineering, Lehigh University

November 14, 2005

Introduction

This report outlines the status of the research on the design of an energy dissipation (ED) device for a self-centering moment resisting frame (SC-MRF) steel connection, including the preliminary design, current experimental work, and future analytical work.

As presented at the US-Taiwan Workshop on Self-Centering Structural Systems in June 2006, the criteria used to evaluate several ED devices include effective energy dissipation capability, device constructibility, and life-cycle and maintenance characteristics. The bottom flange friction device (BFFD) was chosen for more in-depth analysis and experimentation due to its simplicity of construction and installation and good energy dissipation characteristics. A schematic of the BFFD is shown in Fig. 1. The BFFD consists of a vertically oriented slotted plate shop welded to the bottom beam flange as well as two outer "angles" field bolted to the column. Sandwiched between the two outer angles are brass friction plates on both sides of the beam plate. High strength bolts with disc spring washers provide the normal force, compressing the entire assembly together.

The BFFD can be delivered to the site attached to the beam/cover plate, and can be used during erection of the beam, prior to the post-tensioning operation. Since the device is located on the bottom flange only, there is no interference with the composite slab.

(a) BFFD Status Report 1 Nov 2005.pdf

Experimental Evaluation of a Bottom Flange Friction Device for a Self-Centering Seismic Moment Resisting Resistant Frame with Post-Tensioned Steel Moment Connections

by

Michael E. Wolski

A Thesis
Presented to the Graduate and Research Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science

in
Civil Engineering

Lehigh University
May 2006

(b) M. Wolski Thesis.pdf

4th International Conference on Earthquake Engineering
Taipei, Taiwan
October 12-13, 2006
Paper No. 108

POST-TENSIONED MOMENT CONNECTIONS WITH A BOTTOM FLANGE FRICTION DEVICE FOR SEISMIC RESISTANT SELF-CENTERING STEEL MRFS

J. M. Ricles[1], R. Sause[2], M. Wolski[3], C.Y. Seo[4], and J. Iyama[5]

ABSTRACT

New earthquake resistant structural steel moment resisting frame (MRF) systems are being developed by a research group led by Lehigh University in collaboration with Nazarian and Purdue Universities under the NSF funded Network for Earthquake Engineering Simulation Research (NEESR) program. These innovative self-centering (SC) structural systems are designed to be damage free under the design basis earthquake (DBE). This paper presents the results of experimental studies on a post-tensioned friction connection for a self-centering moment resisting frame (SC-MRF). The connection consists of a friction device placed below the beam bottom flange, in order to avoid interference with the composite slab, with post-tensioned high strength strands running parallel to the beam. Tests on the connection show it to possess excellent deformation capacity, dissipate inelastic deformations in other elements of the connection, and return the structure to its pre-earthquake position. The results of the experimental studies are presented. Based on the experimental results, analytical models were developed in OpenSees. The formulation for these and a comparison with the experimental behavior of the connection are presented.

Keywords: Friction, Post-tensioning, Self-Centering Moment Resisting Frame, Steel Moment Connection

INTRODUCTION

Damage to conventional steel moment resisting frames (MRFs) in recent earthquakes has prompted innovative design and construction methods. As an alternative to welded construction, Ricles et al. (2001) developed a post-tensioned (PT) steel beam-to-column moment connection utilizing high-strength steel strands running parallel to the beam with bolted top and bottom seat angles. Under

[1] Joseph R. Morgan Professor of Structural Engineering, ATLSS Center, Dept. of Civil and Environmental Engineering, Lehigh University, PA, USA, jmr3@lehigh.edu
[2] Joseph T. Stuart Professor of Structural Engineering, ATLSS Center, Dept. of Civil and Environmental Engineering, Lehigh

(c) 4ICEE conference paper No.108.pdf

Figure 5.4 Files for Publications

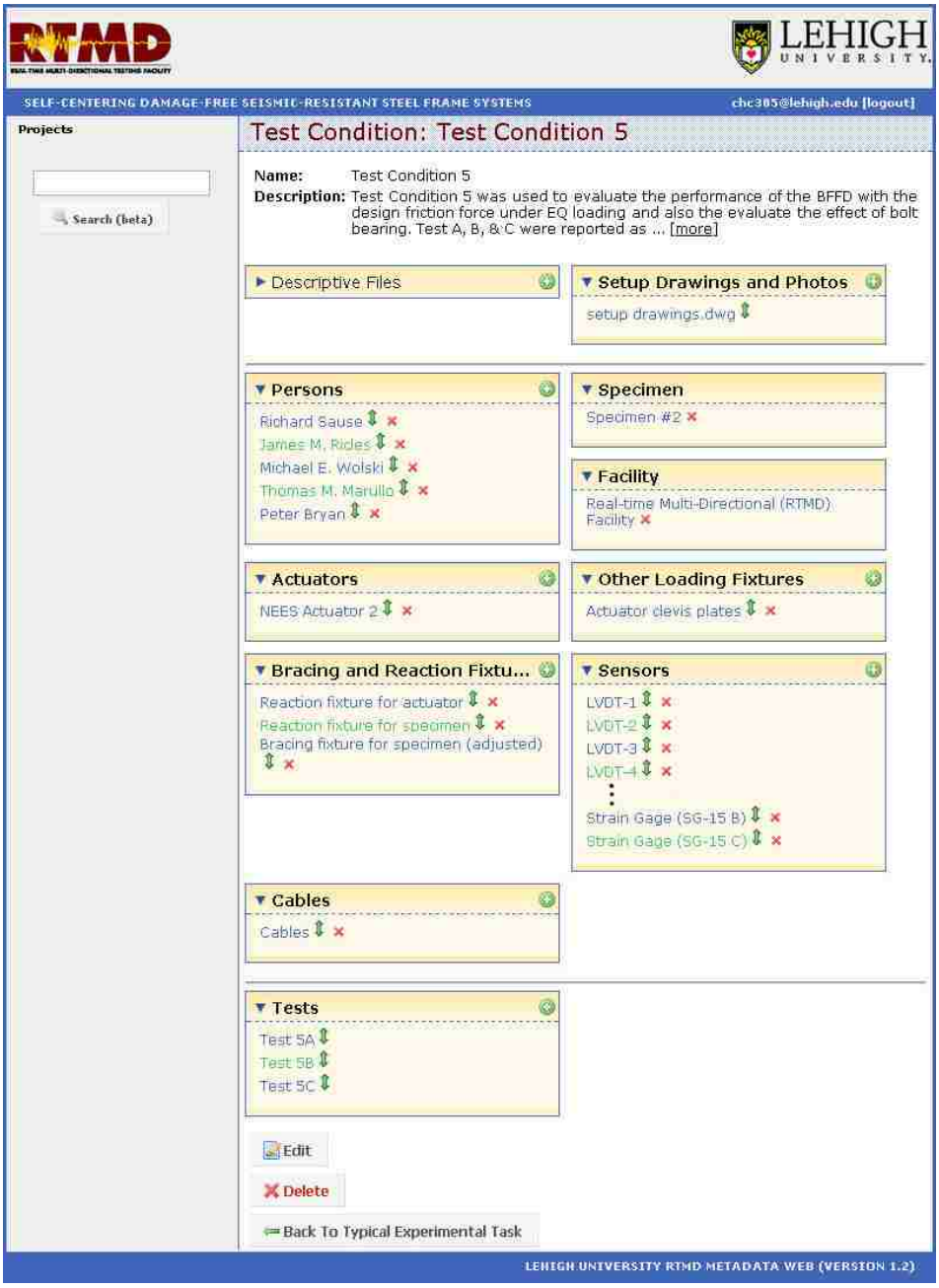


Figure 5.5 Test Condition 5 Web Page

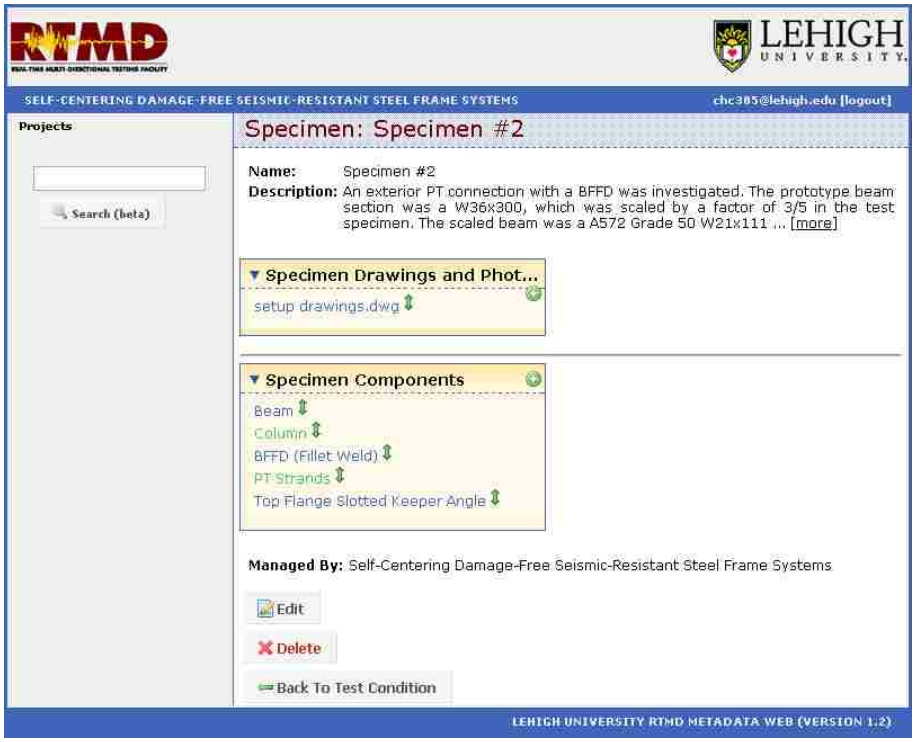


Figure 5.6 Specimen # 2 Web Page

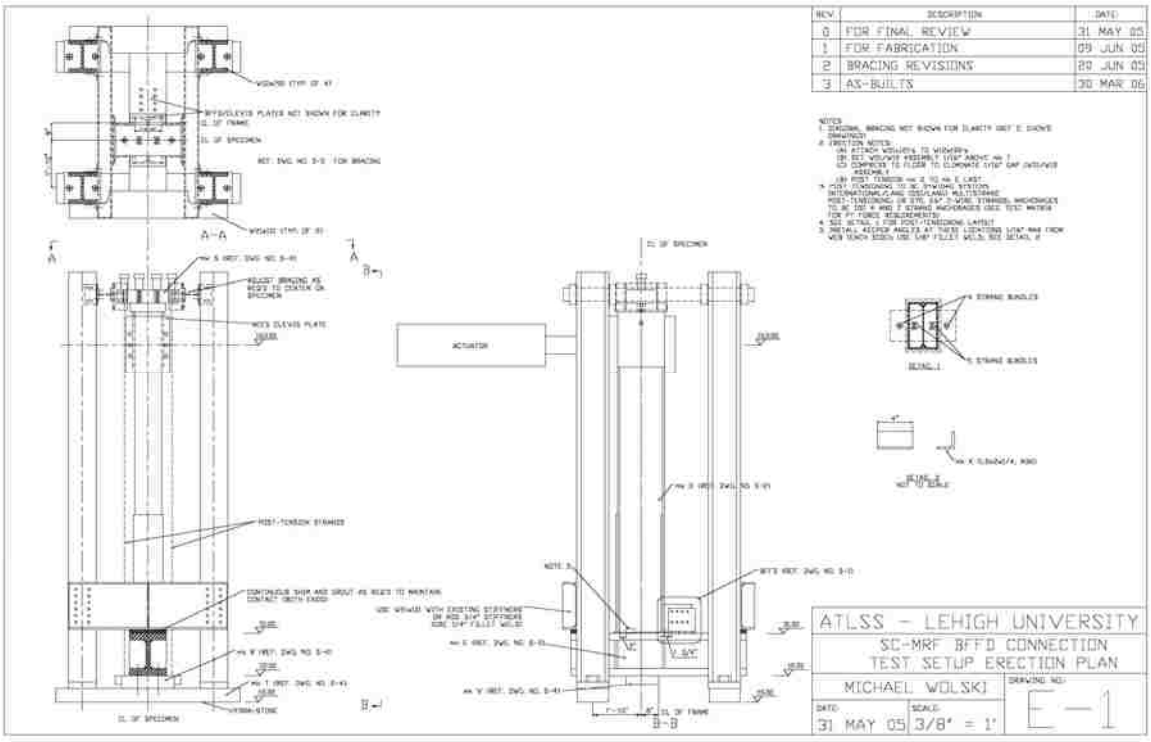


Figure 5.7 Tab E-1 of Setup Drawing File

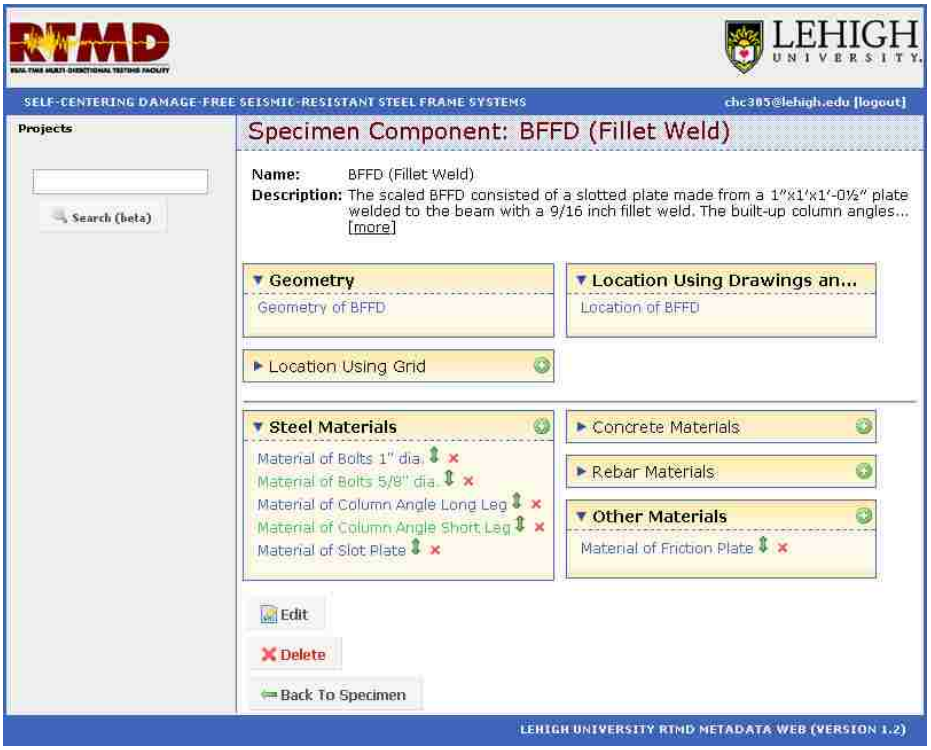


Figure 5.8 BFFD (Fillet Weld) Web Page

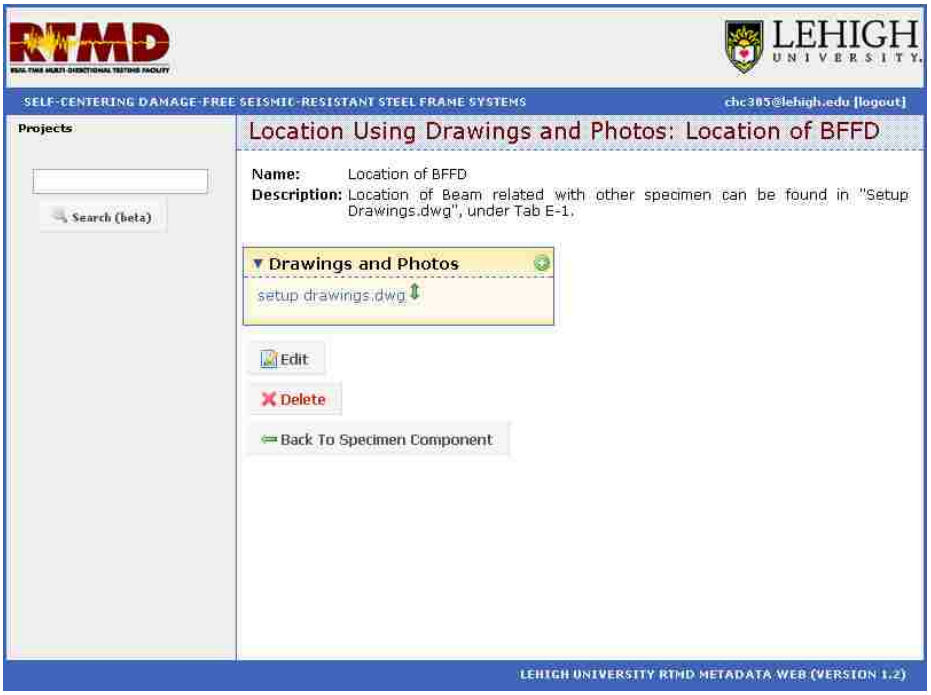


Figure 5.9 Location of BFFD Web Page

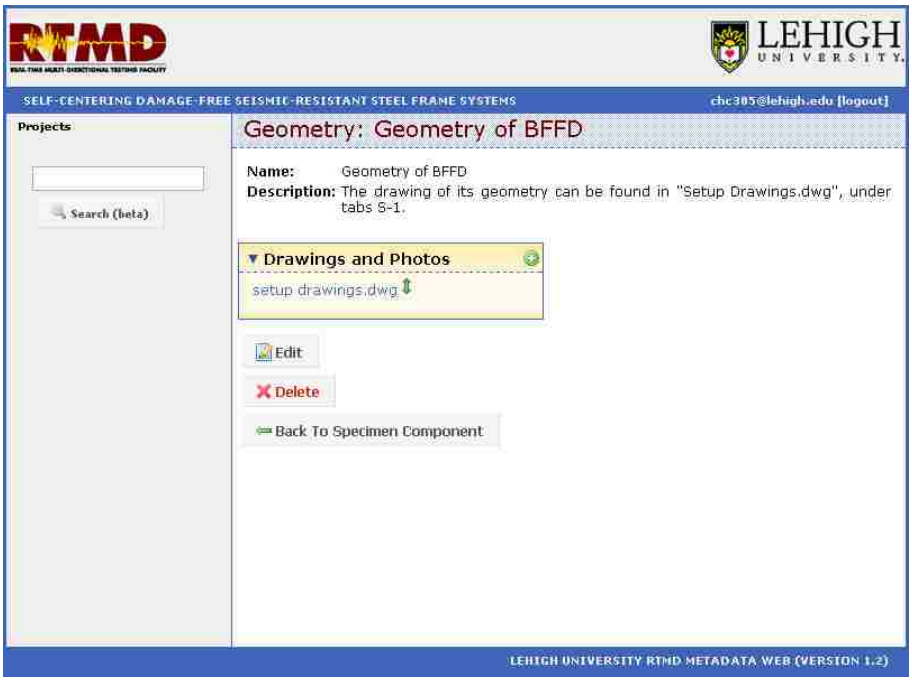


Figure 5.10 Geometry of BFFD Web Page

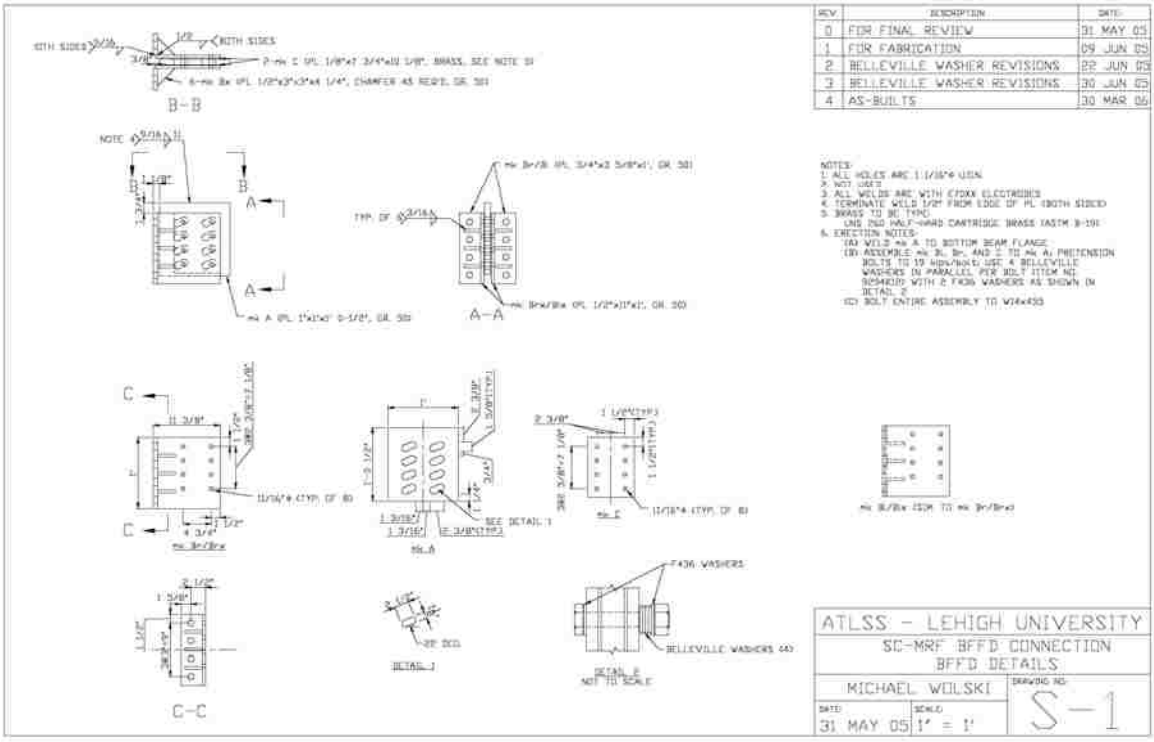


Figure 5.11 Tab S-1 of Setup Drawing File

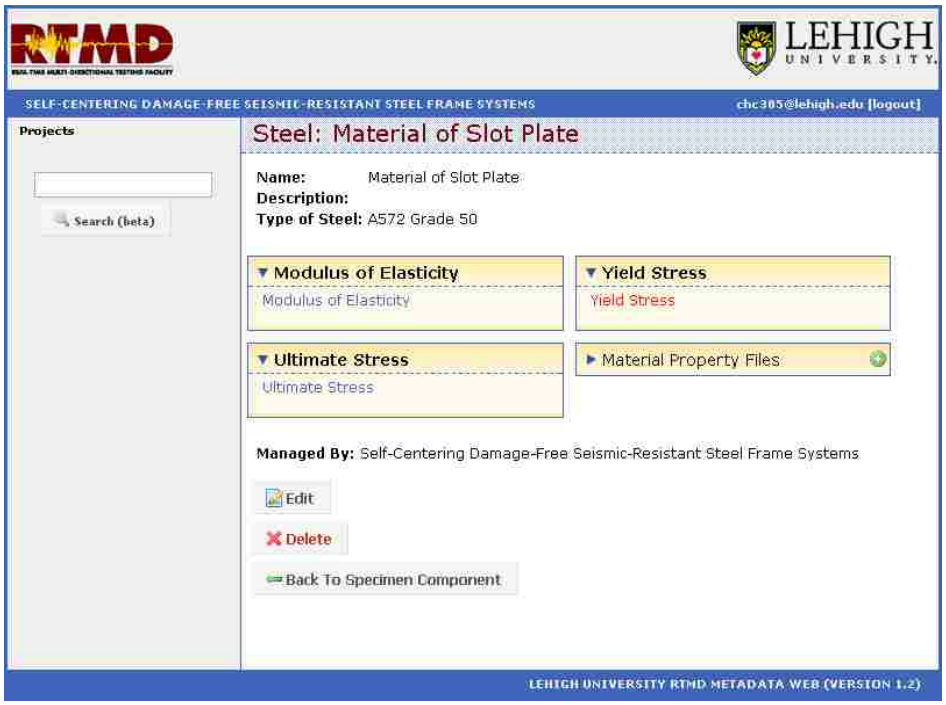


Figure 5.12 Material of Slot Plate Web Page

Figure 5.13 Yield Stress Web Page

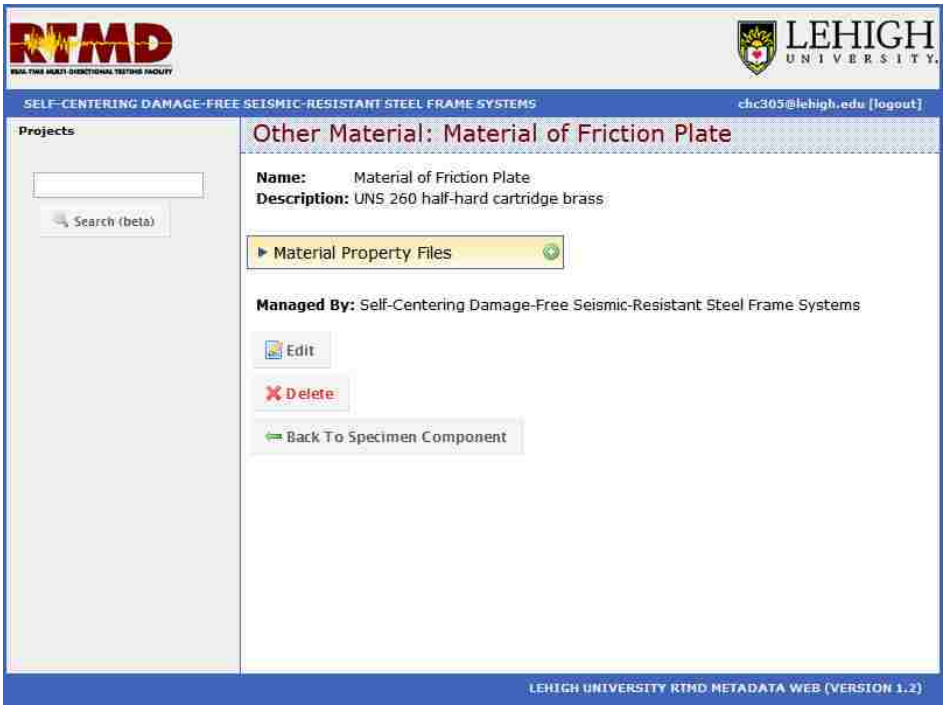


Figure 5.14 Material of Friction Plate Web Page

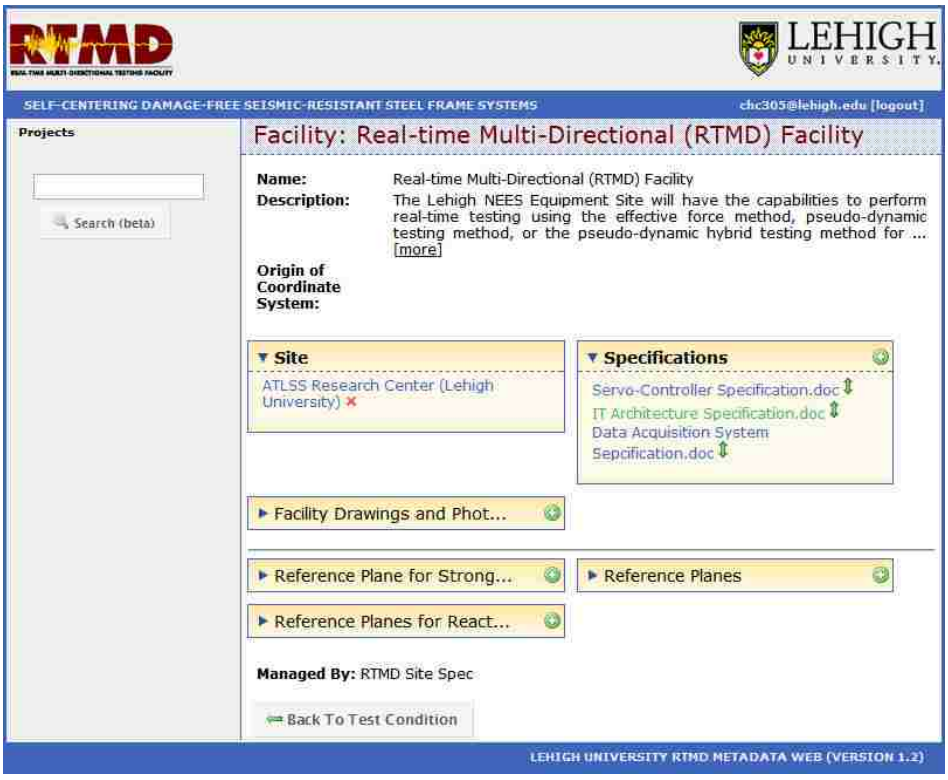


Figure 5.15 Real-Time Multi-Directional (RTMD) Facility Web Page

The servo controller (DCI 2000, and referred to herein as Controller), communicates with all of the servo-valves, actuators, transducers, HAM control box and simulation computer (RTMDctrl) as part of the servo-control system. The Controller consists of the following components:

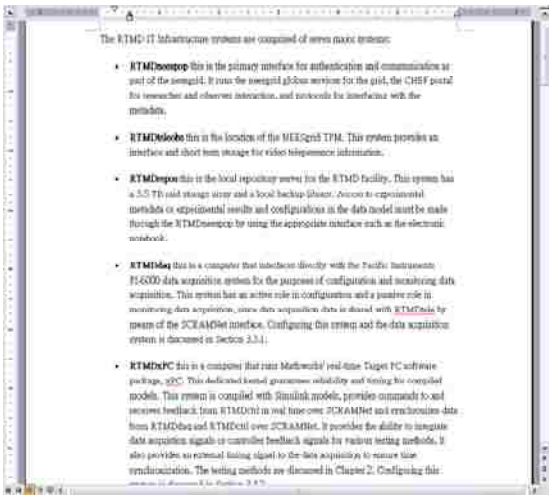
•The Host Computer running Windows 2000 (referred to in this Guide as RTMDctrl), is an Intel bus-based system including a high resolution graphics subsystem driving a high quality color monitor, serial and parallel subsystem which handles keyboard, printer and mouse devices, a DCSI or IDE high capacity hard disc and at least 128MByte of memory with cached processor memory subsystem. The software for system control is called *Adaptor* which consists of a series of modules such as: Control, Monitor, Limits, Database, OmniScope, Data Logger, Reply, Filter, Wavegen, etc. A PID control module is built in. For developing a user's control law, implementation is achieved through Socket building. Matlab-Simulink is used to program the user's control law and Real-Time Workshop is used to generate C-code, which is loaded into the database by the Socket Wizard. Thus, a user's control law can be implemented, including a simulation using bumpless off mode.

•The Controller consist of a Digital Signal Processor (DSP) Real-time Control Card (Module 2201), which is plugged into the RTMDctrl. The card contains a TMS320C30 DSP to deliver sustained (33MFLOP) performance in real time, local memory, and a high speed Host Master Interface to RTMDctrl. The DSP can control up to 16 actuators. Sampling rate is set at 1024Hz.

•Two External Conditioning 'XBus' Subsystems. These enclosures are connected to the DSP Controller at RTMDctrl via shielded high speed bus-cables. The XBus systems each contain redundant power supplies and a backplane bus into which are plugged various transducer cards. All analogue channels have individual 16 bit resolution ADC or DAC systems which control simultaneously to improve throughput and eliminate signal skews. The cards installed for the five actuators are:

o Five 2202 0 conditioner cards, which process transducer signals, converting them

(a) Servo-Controller Specification.doc



The RTMD IT Infrastructure systems are comprised of seven major systems:

- **RTMDnsnspop** this is the primary interface for authentication and communication as part of the neesgrid. It runs the neesgrid gridfour services for the grid, the CHEF portal for researcher and observer interaction, and protocols for interfacing with the metadata.
- **RTMDtelesbo** this is the location of the MEEQpro TPM. This system provides an interface and short term storage for video telepresence information.
- **RTMDnepos** this is the local repository server for the RTMD facility. This system has a 5.5 TB raid storage array and a local backup library. Access to experimental metadata or experimental results and configurations in the data model must be made through the RTMDnespop by using the appropriate interface such as the electronic notebook.
- **RTMDdaq** this is a computer that interfaces directly with the Pacific Instruments PI-6000 data acquisition system for the purposes of configuration and monitoring data acquisition. This system has an active role in configuration and a passive role in monitoring data acquisition, since data acquisition data is shared with RTMDnfs by means of the SCRAMNet interface. Configuring this system and the data acquisition system is discussed in Section 3.3.1.
- **RTMDxPC** this is a computer that runs Mathworks' real-time Target PC software package, xPC. This dedicated kernel guarantees reliability and timing for compiled models. This system is compiled with Simulink models, provides commands to and receives feedback from RTMDctrl in real time over SCRAMNet and synchronizes data from RTMDdaq and RTMDctrl over SCRAMNet. It provides the ability to integrate data acquisition signals or controller feedback signals for various testing methods. It also provides an external timing signal to the data acquisition to ensure time synchronization. The testing methods are discussed in Chapter 2: Configuring this

(b) IT Architecture Specification.doc

The DAQ Mainframe (also referred to as the 6000DAS) is a high-speed data acquisition and conditioning system that acquires data from strain gauges, accelerometers, LVDTs, and thermocouples. The DAQ Mainframe consists of three enclosures housing three different types of modules: (1) Model 6013 for LVDTs and thermalcoupleg (2) Model 6014 for accelerometers and (3) and Model 6033 for strain gages. There are a total of 9 modules of Model 6013, 5 modules of Model 6014, and 20 modules of Model 6033. Each module conditions 8 channels. The DAQ Mainframe hosts a SCRAMNet card that broadcasts real time data over a fiber optical network to the RTMDctrl and/or RTMDxPC for integrated simulation and control and to the RTMDdaq for telepresence. Below is a summary of the description, features, and configuration for the 6000DAS and specifications for the modules for model 6013, 6014, and 6033.

6000DAS description:

- **Automated signal conditioning and calibration**
- **16 bit resolution, simultaneous sample & hold**
- **±0.03% accuracy**
- **1M samples per second with up to 100K per channel**
- **History buffer that preserves post data for failure analysis**
- **Fast, hardware-based warnings and alarms with automatic responses**

6000DAS features:

(c) Data Acquisition System Sepcification.doc

Figure 5.16 Files for Facility Specifications

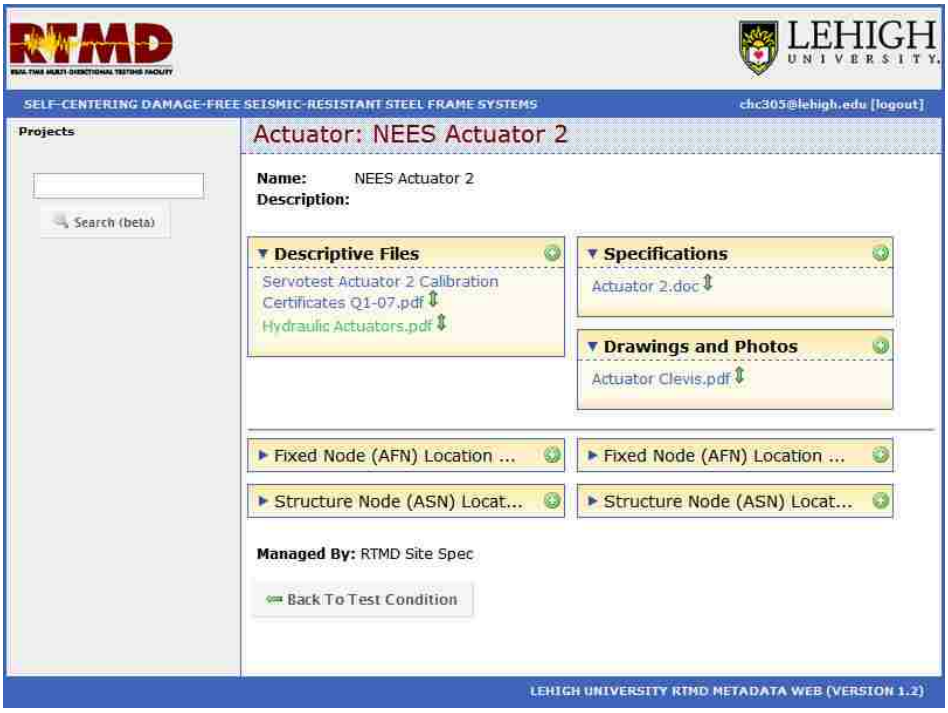
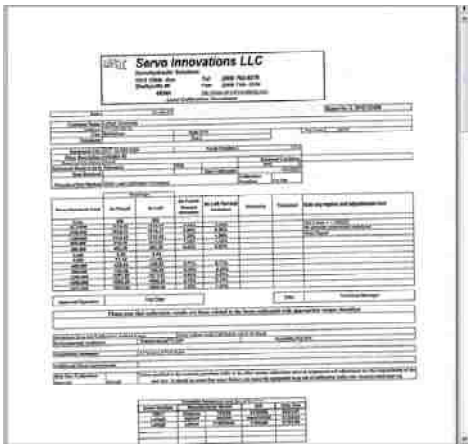


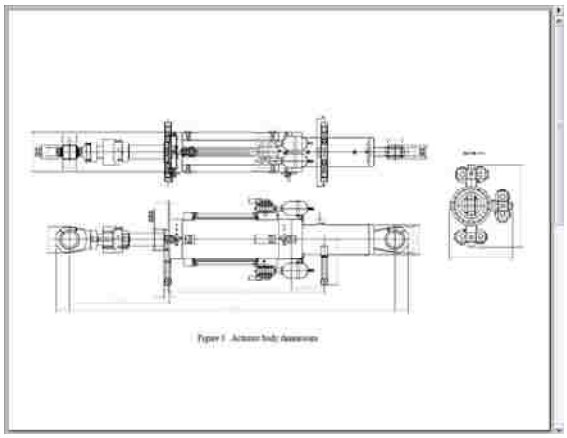
Figure 5.17 NEES Actuator 2 Web Page



(a) Servotest Actuator 2 Calibration Certificates Q1-07.pdf

(b) Hydraulic Actuators.pdf

(c) Actuator 2.doc



(d) Actuator Clevis.pdf

Figure 5.18 Descriptive, Specification, and Drawing Files for NEES Actuator 2

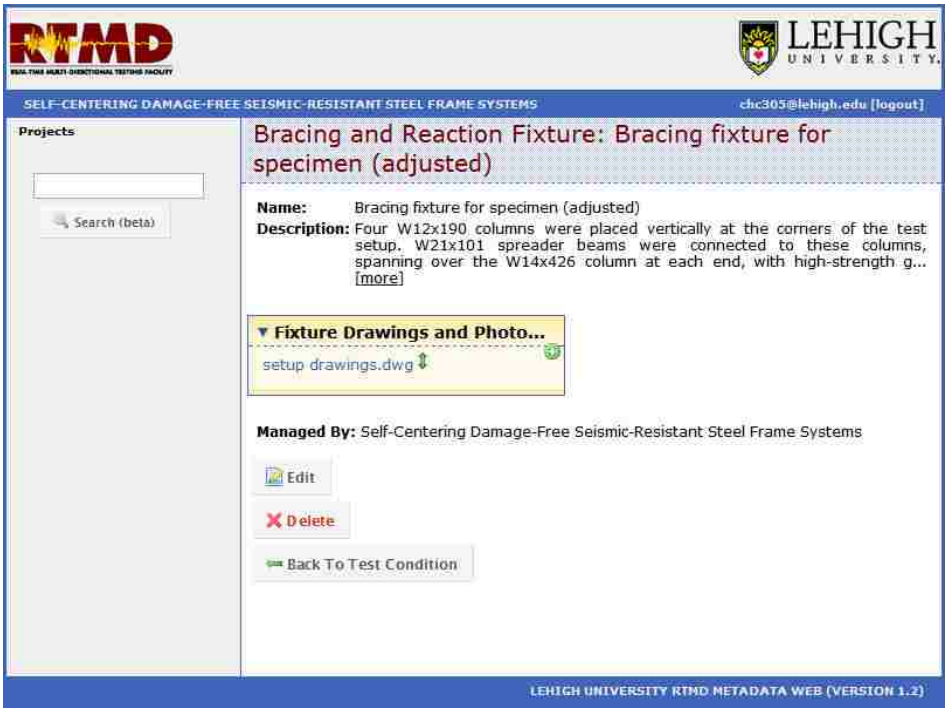


Figure 5.19 Bracing Fixture for Specimen (Adjusted) Web Page

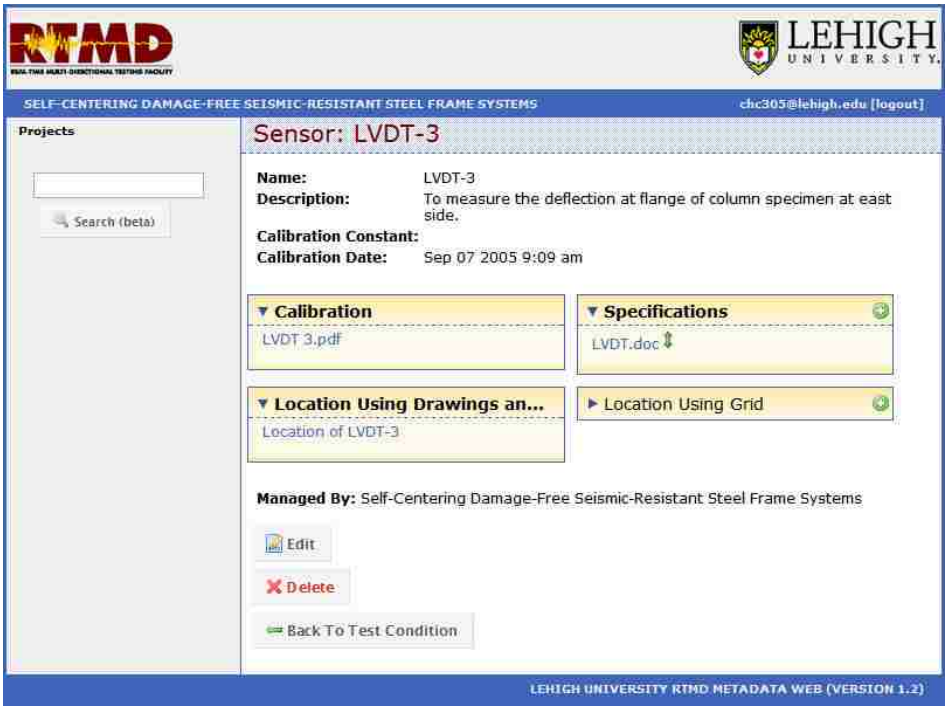
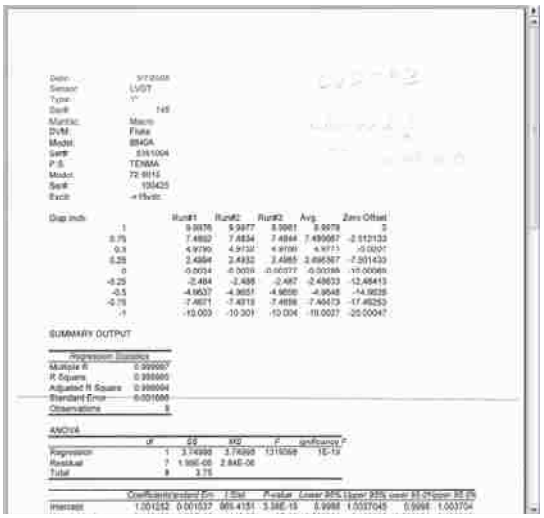
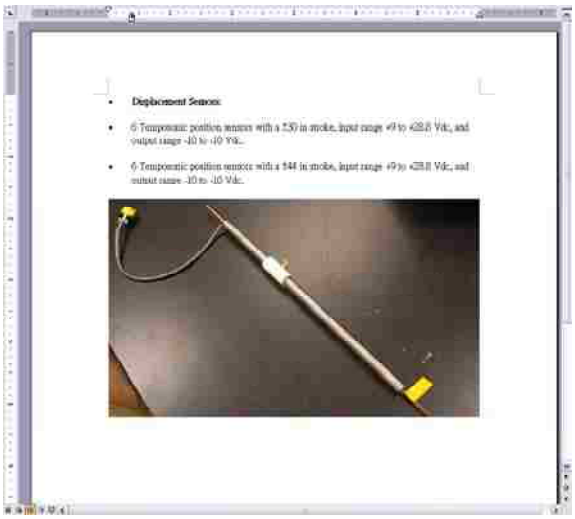


Figure 5.20 LVDT-3 Web Page



(a) LVDT 3.pdf



(b) LVDT.doc

Figure 5.21 File of Calibration and Specification of LVDT-3

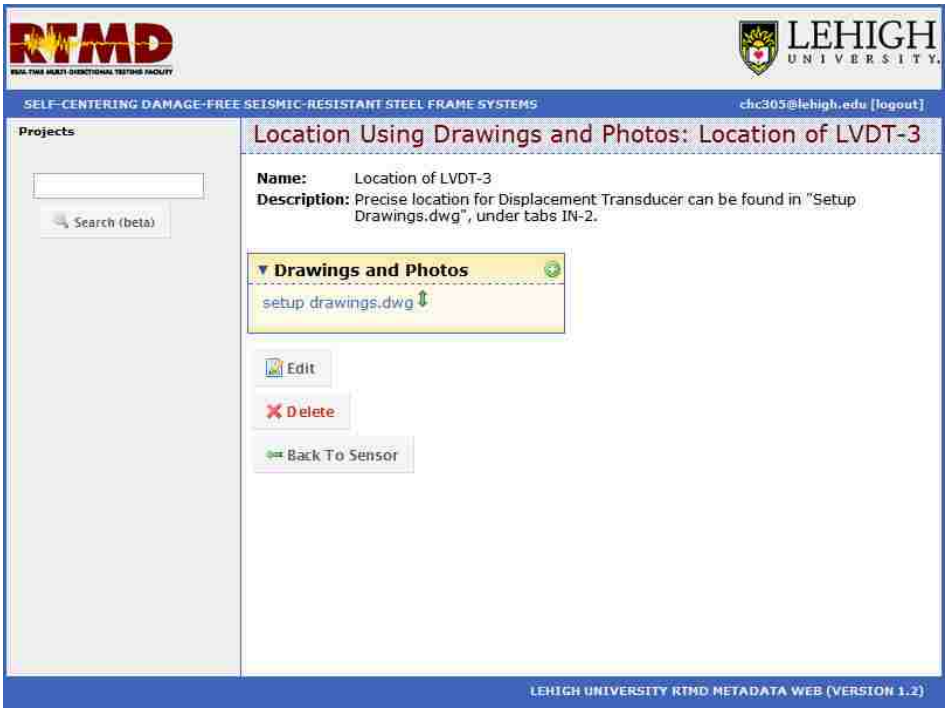


Figure 5.22 Location of LVDT-3 Web Page

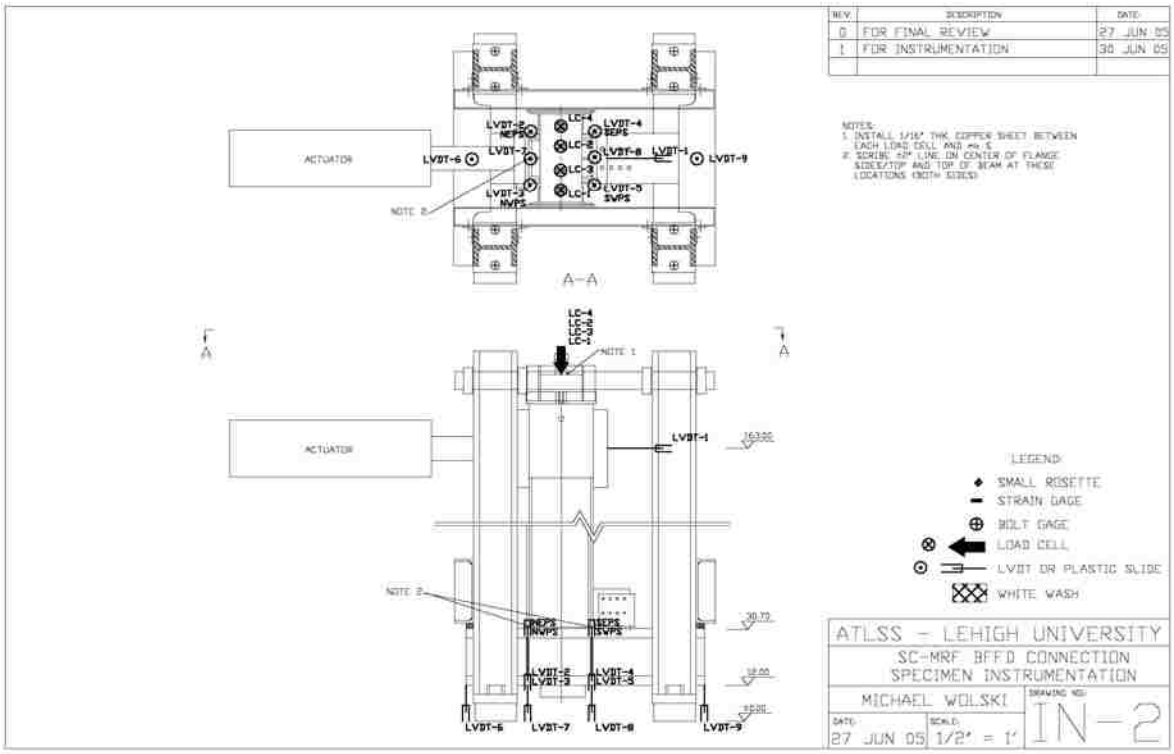


Figure 5.23 Tab IN-2 of Setup Drawing File

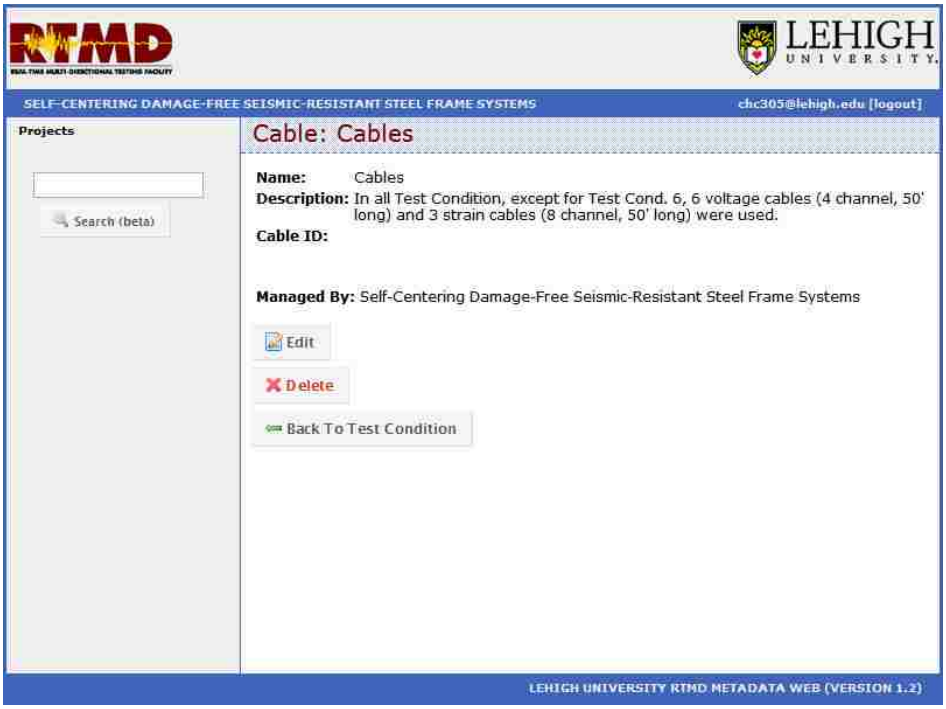


Figure 5.24 Cables Web Page

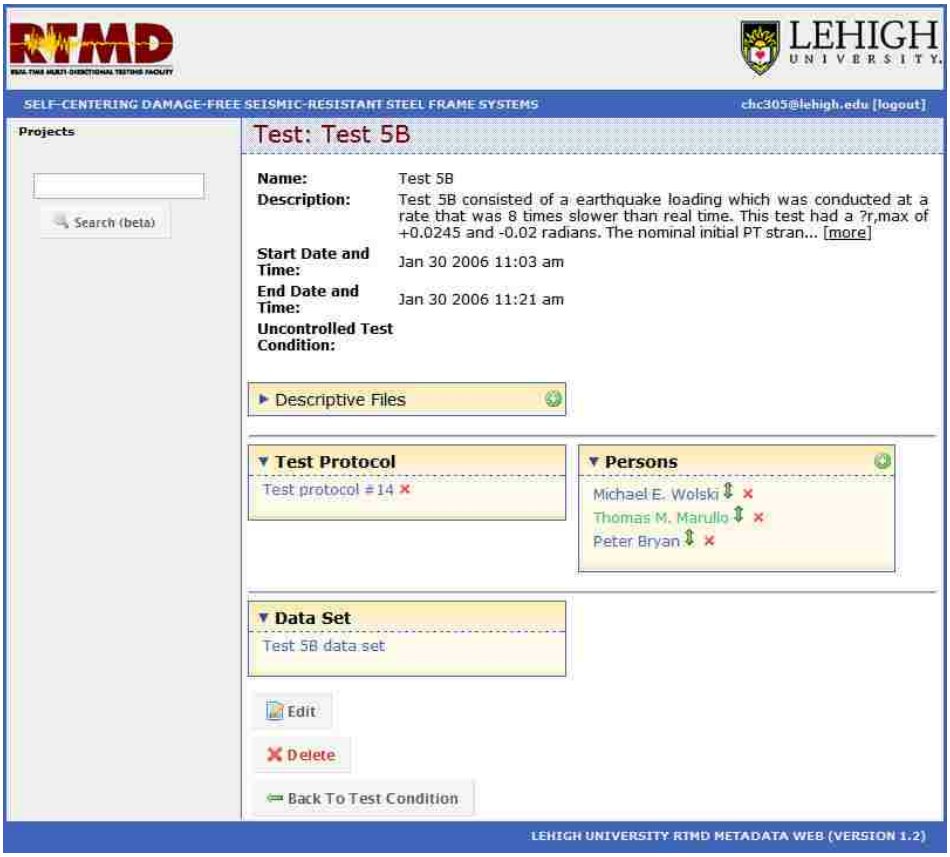


Figure 5.25 Test 5B Web Page

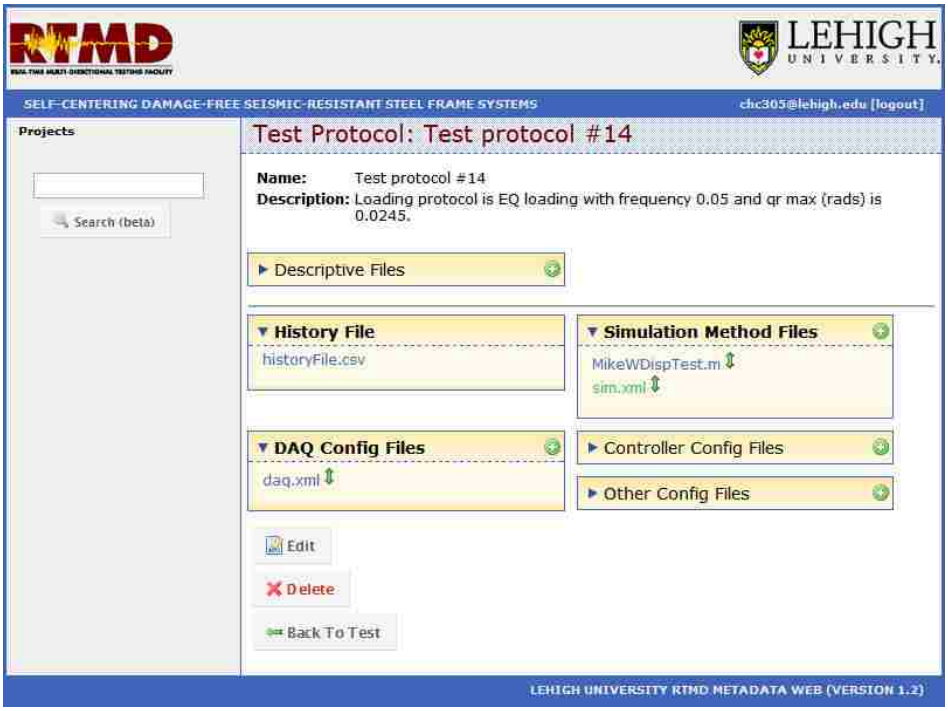


Figure 5.26 Test Protocol # 14 Web Page

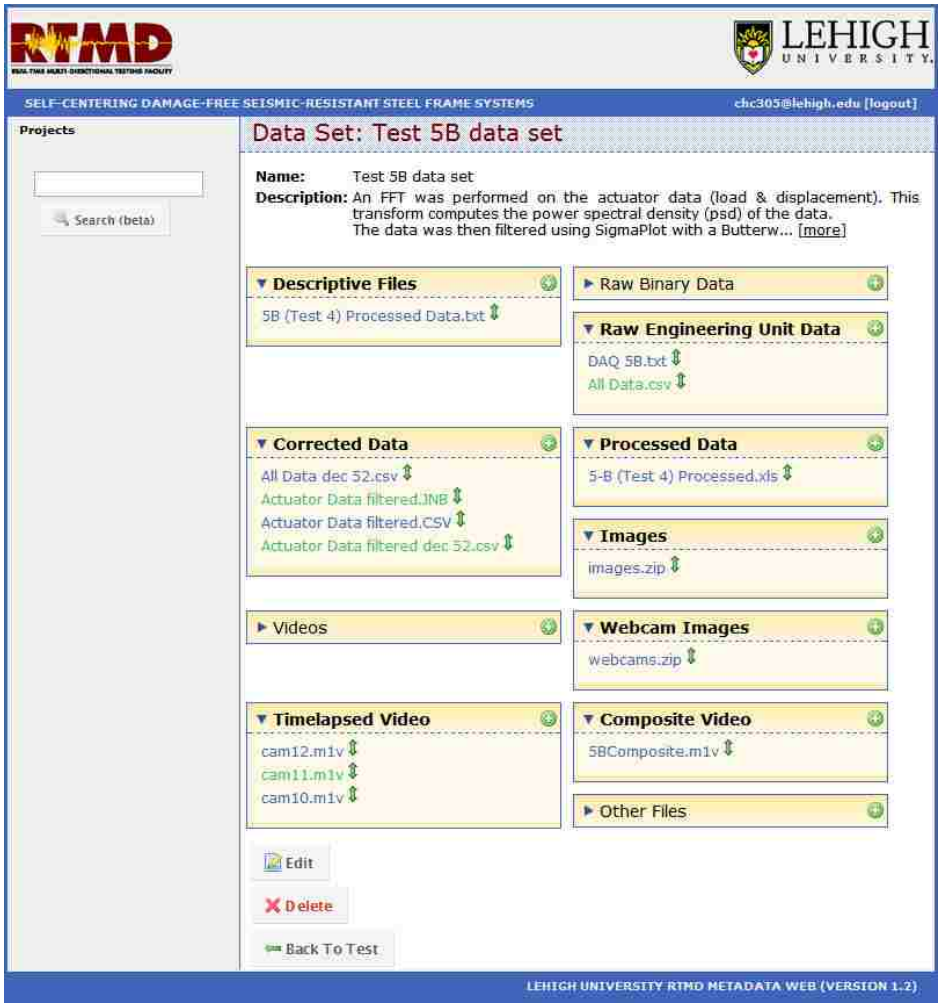


Figure 5.27 Test 5B Data Set Web Page

Chapter 6

Example of Lehigh RTMD Metadata Web Applied to Hybrid Simulation

6.1. Introduction

A project, named the Studies on Large-scale, Real-time Pesudodynamic (PSD) Testing (Mercan, 2007), is used as an example of applying the Lehigh RTMD Metadata Web to a hybrid simulation. The hybrid simulations of this project were conducted at the RTMD earthquake simulation facility. The information and data associated with the selected simulation are organized using the Lehigh RTMD Metadata Web.

6.2. Background of Project

The Studies on Large-scale, Real-time Pseudodynamic (PSD) Testing project (Mercan, 2007) was selected as an example of applying the Lehigh RTMD Metadata Web to a hybrid simulation. The research objectives of this project are to develop a methodology for implementing large-scale, real-time hybrid PSD simulation, performing experiments, and evaluating the simulation results. The hybrid PSD simulation is a displacement-based experimental technique that is used to simulate the seismic response of structures. It utilizes feedback signals from a test structure in a numerical integration algorithm to sequentially solve the equations of motion to determine command displacements. The command displacements are imposed on the test structure using hydraulic actuators. It is advantageous to avoid the cost of fabricating and testing the entire structure. The hybrid PSD simulation includes only a portion of the structure in the laboratory.

The prototype building for the hybrid PSD simulation is a 3 story MDOF shear building with an elastomeric damper in the first story as shown in Figure 6.1. The 3 story MDOF frame is modeled in the Simulink 6.2 as an analytical substructure for the simulation. The elastomeric damper is the physical substructure of the simulation, located in the RTMD earthquake simulation facility. The drawings and photos of the physical substructure setup are presented in Figure 6.2.

A Simulink model is used for the real-time hybrid PSD simulations as shown in Figure 6.3. SUBSYSTEM 1 is the model for the integration algorithm (as well as simulation coordinator in the Lehigh Model) and the analytical substructure. The physical substructure is SUBSYSTEM 2. SUBSYSTEM 2 receives command from the integration algorithm in SUBSYSTEM 1 to control the servo-hydraulic system in the laboratory (which imposes displacement on this physical substructure) and then sends feedback from the physical substructure to SUBSYSTEM 1. SUBSYSTEM 1 then performs a state determination for the analytical substructure. The data from the physical and analytical substructures are combined and the integration algorithm computes the next command/displacement.

6.3. Information and Data in Lehigh RTMD Metadata Web

The data and information related to the selected project has been organized using the Lehigh RTMD Metadata Web. For simplicity, only selected web pages and related files are presented for this application example. The information and data are presented in the five main levels of the Lehigh Model.

6.3.1. Project Class Level and Experimental Task Class Levels

The information about the project and the hybrid experimental task is presented in the web pages shown in the Figures 6.4 and 6.5, which represent objects of the project class and the hybrid experimental task class of the Lehigh Model, respectively. In the Studies on Large-scale, Real-time Pseudodynamic (PSD) Testing project web page, a concise description about the project and its research objectives is given. A file containing the researcher's dissertation shown in Figure 6.6a can be accessed from the publications attribute to provide more detailed information regarding this project. Figure 6.4 shows that the project contains two typical experimental tasks and two hybrid experimental tasks, the Hybrid PSD Test with MDOF Analytical Substructure Task is the selected example of an application of the Lehigh RTMD Metadata Web to a hybrid simulation. In the Hybrid PSD Test with MDOF Analytical Substructure Task web page shown in Figure 5.5, the description briefly summarizes the test method used for this task. A conference paper related to this hybrid experimental task shown in Figure 6.6b can be accessed from the publications attributes. Only one simulation coordinator, one analytical substructure, and one physical substructure are used for this hybrid experimental task as shown in Figure 6.5.

6.3.2. Test Condition Class Level

The Target PC web page shown in Figure 6.7 represents an object of the simulation coordinator class of the Lehigh Model. The description and descriptive files provide detailed information about the simulation coordinator. The software used to conduct this experiment is called xPC, as shown in Figure 6.7. The object link in the model

attribute provides access to the Integration Algorithm web page shown in Figure 6.8 to represent information about the model used for this simulation coordinator. A description of the model is given. The model file can be accessed from the model file attribute. As described in Section 6.2, the simulation coordinator and the analytical substructure are contained in one model for this hybrid PSD simulation. A file in the visual files attribute indicates that SUBSYSTEM 3 in the model is used for the simulation coordinator as shown in Figure 6.9. The simulation coordinator for this hybrid PSD simulation is located in the Real-Time Multi-Directional (RTMD) facility, as shown in Figure 6.7. The information about this facility is the same as described in the example in Chapter 5.

The 3 Story Substructure web page shown in Figure 3.10 represents an object of the analytical substructure class of the Lehigh Model. The description and descriptive files provide information about this analytical substructure. Simulink 6.2 is the software used to model the analytical substructure for this hybrid simulation. The information about the analytical substructure model is represented in the 3 DOF frame web page shown in Figure 6.11. The description briefly describes the model. The model file can be accessed from the model files attribute. A file is provided through the visual files attribute to indicate that Embedded Function 1 in the model is used for the analytical substructure as shown in Figure 6.12. The analytical substructure for this hybrid PSD simulation is located in the Real-Time Multi-Directional (RTMD) facility as shown in Figure 6.10.

The Damper Testbed web page in Figure 6.13 represents an object of the physical substructure class of the Lehigh Model. A description of this physical substructure is given. An AutoCAD file in the setup drawings and photos attributes provide an illustration of the physical substructure setup in the laboratory as shown in Figure 6.2a. Detailed information about the Damper Specimen is represented in the Damper Specimen web page shown in Figure 6.14. The web page includes a description, and drawings and photos for the specimen. The value of the facility attribute indicates that this physical substructure is located in the Real-Time Multi-Directional (RTMD) facility as shown in shown in Figure 6.13. NEES Actuator 2 is used for this physical substructure. The information about this actuator is presented in the example in Chapter 5. Examples of the information about the bracing and reaction fixtures and other loading fixtures used for this physical substructure setup are presented in Figures 6.15 and 6.16.

6.3.3. Test Class Level

The information about a simulation and related analytical substructure computations and physical substructure tests is represented in the web pages shown in Figures 6.17 to 6.19, which represent objects of the simulation class, the analytical substructure computation class, and the physical substructure test class of the Lehigh Model, respectively. The MDOF (KFF=2) Simulation web page shown in Figure 6.15 contains information about the simulation and the relationship among related analytical substructure computations and physical substructure tests. The object link in the interfaces to analytical substructure computations attribute provides access to the Linear MDOF 3 Story Substructure web page shown in Figure 6.20, which represents an object of the analytical

sub. interface class of the Lehigh Model. This web page contains the command and feedback signals between the simulation and the related analytical substructure computation. The information about the analytical substructure computation can be accessed from the computation attribute, which links to the web page shown in Figure 6.18. The Linear MDOF (KFF=2) Computation web page (in Figure 6.18) also links to the Linear MDOF 3 Story Substructure web page (in Figure 6.20) from the link in the interface to simulation attribute. Similarly, the link in the interfaces to physical substructure tests attribute (in Figure 6.17) provides access to the Linear MDOF Damper Testbed web page shown in Figure 6.21. This page contains the command and feedback signals between the simulation and the related physical substructure test. The information about the physical substructure test can be accessed from the physical substructure test attribute, which links to the web page shown in Figure 6.19. The Linear MDOF (KFF=2) Test web page (in Figure 6.19) also links to the Linear MDOF Damper Testbed web page (in Figure 6.21).

6.3.4. Test Data Set Class Level

For each hybrid simulation, the experimental data is stored in the web pages shown in Figures 6.22 to 6.24. The web pages shown in Figures 6.22 and 6.23 represent objects from the analytical data set class of the Lehigh Model. The Data Set web page for the simulation (in Figure 6.22) includes the output files from the hybrid simulation. The Data Set web page for the computation (in Figure 6.23) includes the output files from the associated analytical substructure computation. The Data Set web page for the physical test shown in Figure 6.24 represents an object of the experimental data set class of the

Lehigh Model. This web page contains the experimental data, such as raw data, images, and videos, from the associated physical substructure test.

6.4. Summary

A hybrid simulation is used as an example of applying the Lehigh RTMD Metadata Web. The selected project was the Studies on Large-scale, Real-time Pseudodynamic (PSD) Testing project. The Lehigh RTMD Metadata Web example was presented using figures showing the information and data related to the selected simulation. Information on the project and a typical experimental task was shown on web pages at the project class level and the experimental task class level. The simulation coordinator, analytical substructure, and physical substructure setups are represented in web pages at the test condition class level. The simulations with the related analytical substructure computations and the related physical substructure tests are presented on web pages at the test class level. The relationships between the simulation and the related analytical substructure computations, and the simulation and the related physical substructure tests are also presented at the test class level. The resulting data, such as raw data, processed data, and images and videos and output files, are presented on web pages at the data set level.

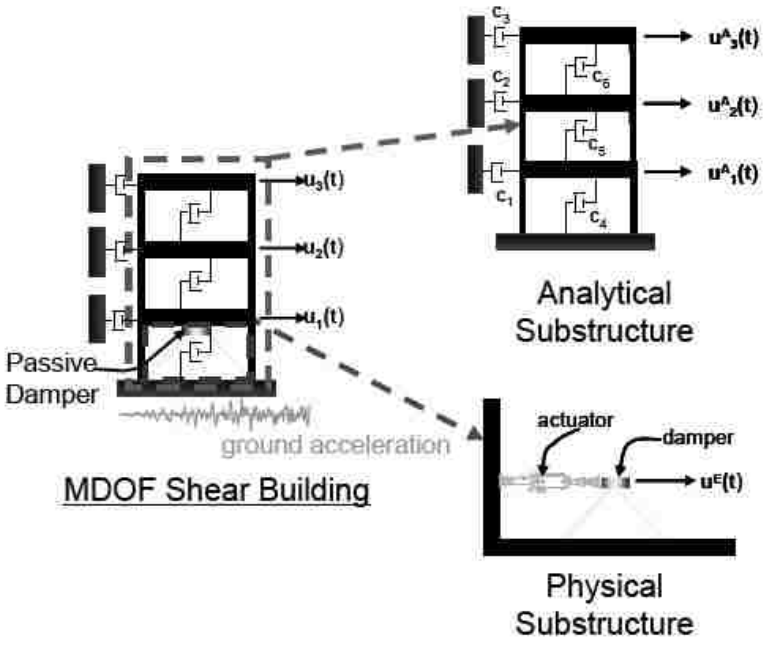
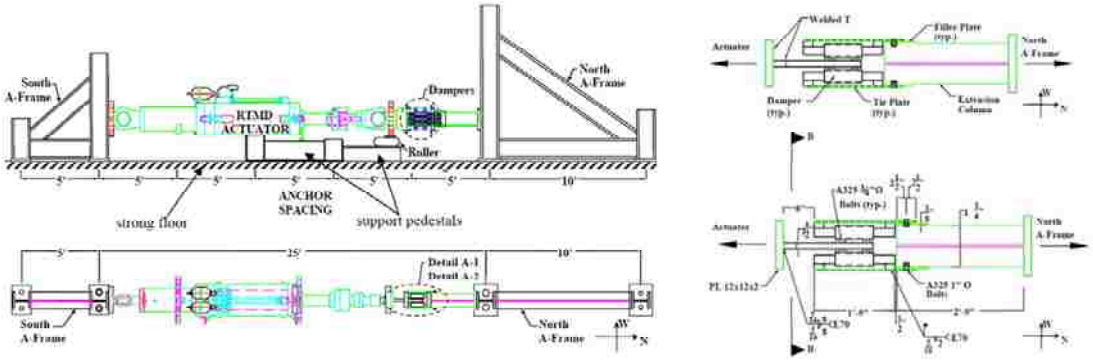


Figure 6.1 MDOF Real-time Hybrid PSD Simulation (Adopted from Mercan, 2007)



a. Drawing of Physical Substructure Setup

b. Photo of Physical Substructure Setup

Figure 6.2 Physical Substructure Setup (Adopted from Mercan, 2007)

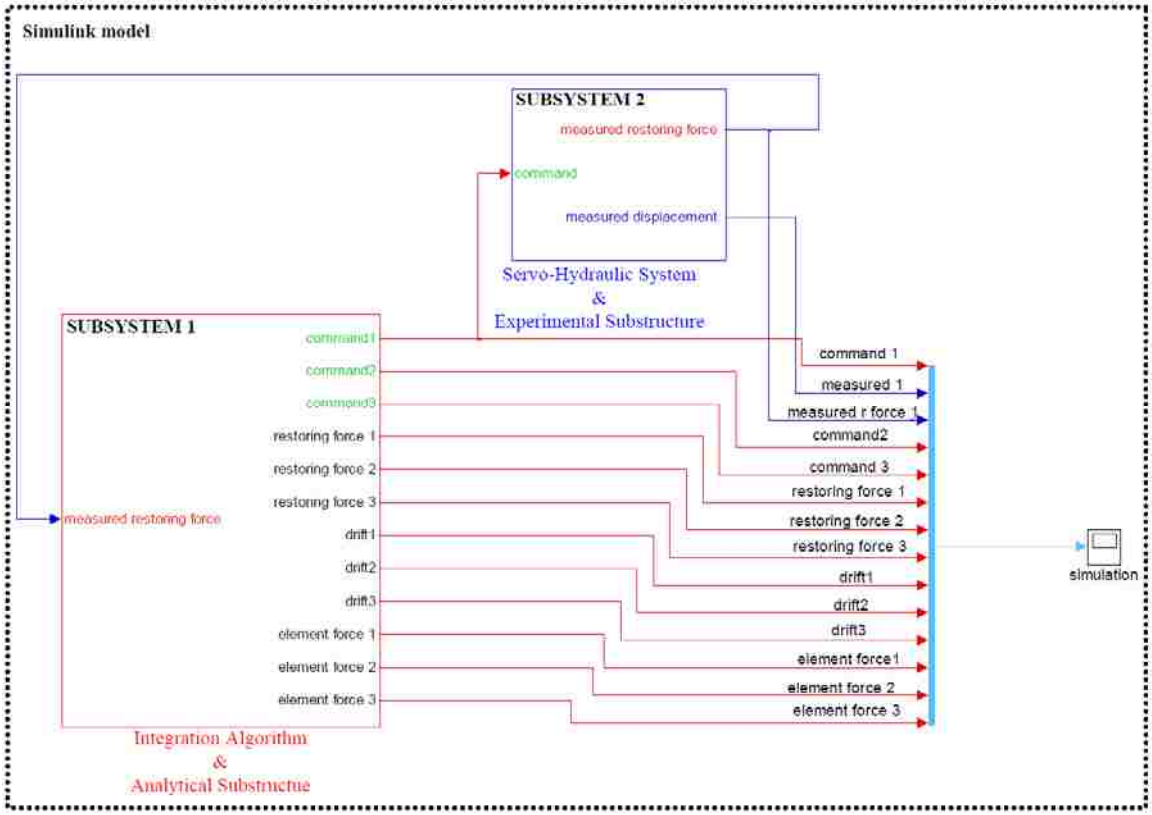


Figure 6.3 Simulink Model for Real-Time Hybrid PSD Simulation with MDOF Analytical Substructure and an Elastomeric Damper as Physical Substructure (Adopted from Mercan, 2007)

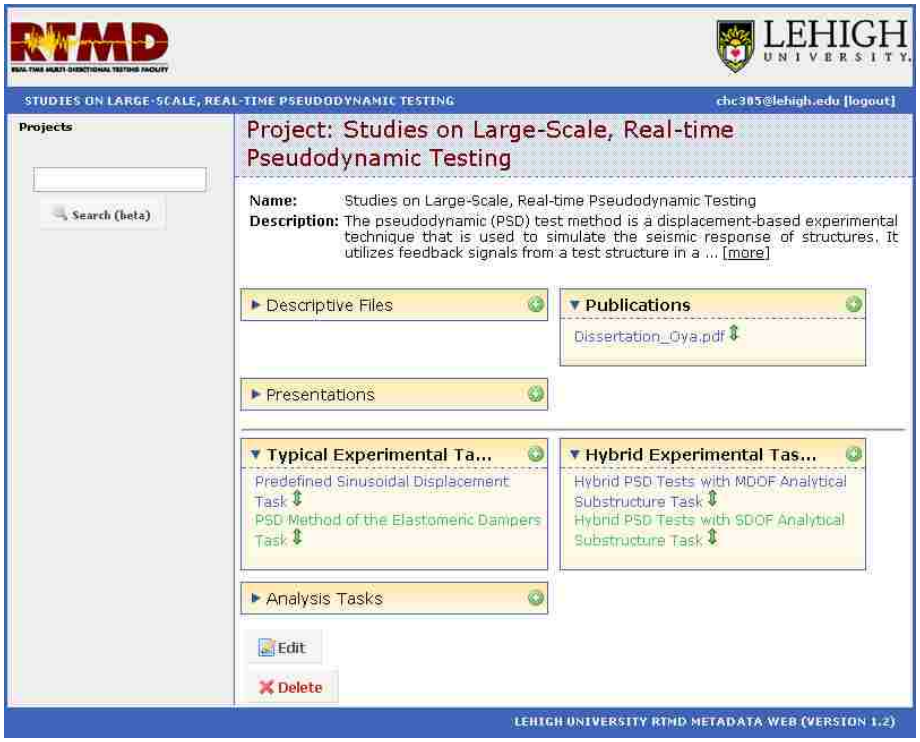


Figure 6.4 Studies on Large-Scale, Real-Time Pseudodynamic Testing Web Page

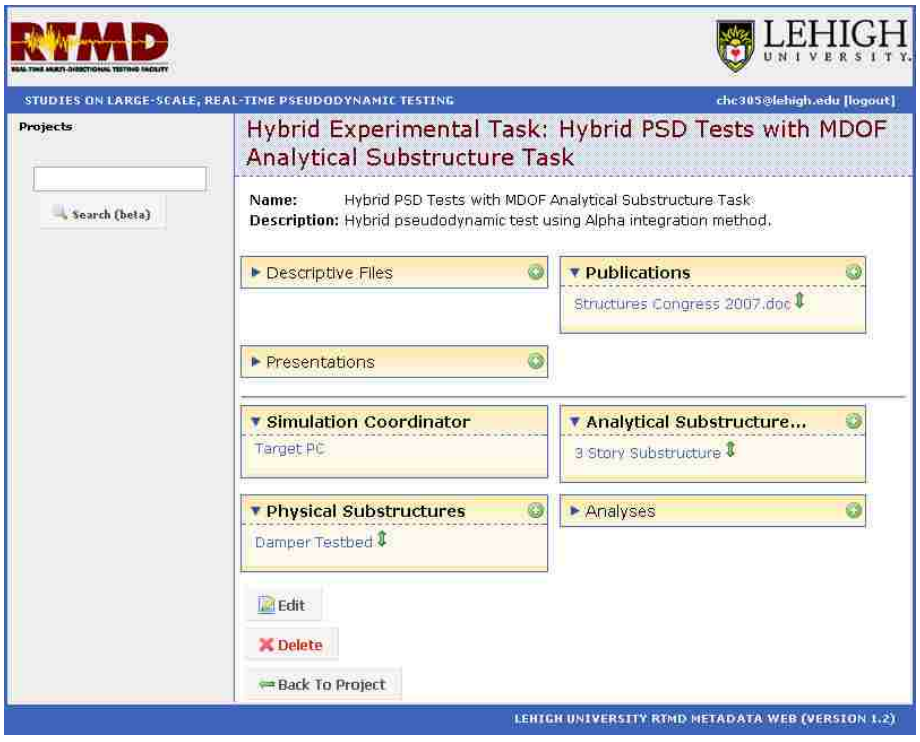


Figure 6.5 Hybrid PSD Tests with MDOF Analytical Substructure Task Web Page

Analytical and Experimental Studies on Large Scale
Real-time Pseudodynamic Testing

by

Oya Mercan

Presented to the Graduate and Research Committee
of Lehigh University
in Candidacy for the Degree of
Doctor of Philosophy

in
Department of Civil and Environmental Engineering

Lehigh University

May, 2007

a. Dissertation_Oya.pdf

Implementation of Real-time Hybrid Pseudodynamic Test Method for Evaluating Seismic Hazard Mitigation Measures

Authors:

Oya Mercan, Lehigh University, 117 ATLSS Drive, ATLSS Center, Bethlehem , PA 18015, oym2@lehigh.edu
James M. Ricles, Lehigh University, 117 ATLSS Drive, ATLSS Center, Bethlehem , PA 18015, jmr5@lehigh.edu

ABSTRACT

Real-time hybrid pseudodynamic (PSD) testing of a 3-story steel moment resisting frame (MRF) equipped with elastomeric dampers at the first floor is presented. The components of the servo-hydraulic integrated control system of the NEES Real-time Multi-directional (RTMD) Earthquake Simulation Facility at Lehigh University are described, along with the analytical substructure modeling, experimental substructure properties and the experimental setup. The stability boundary with respect to both the analytical and experimental substructure restoring force delay is evaluated. In order to minimize the delay in the measured restoring force from the experimental substructure, a velocity feed forward component is introduced into the servo-control loop and its contribution is demonstrated both analytically and experimentally. Selected experimental results of real-time hybrid PSD tests are presented.

INTRODUCTION

Introducing properly designed supplemental passive damping devices is an effective means for seismic hazard mitigation of structures. During a seismic event, structural damage can be alleviated by dissipating energy in damping devices. As a result, the lateral drift, the base shear, overturning moment and damage to nonstructural elements are reduced. To develop an understanding of the effectiveness of the use of these devices towards reducing seismic damage in structures, testing of the devices in conjunction with the structural system are required. Because these devices are typically sensitive to the rate of loading, the tests must be performed in real-time.

Hybrid PSD testing is an experimental technique for investigating the dynamic behavior of complex structures. Hybrid testing combines physical testing with numerical simulation (Dermitzakis and Mahin, 1985), and provides a viable alternative for dynamic testing of structural systems. In a hybrid PSD test, the structure to be tested is divided into a physical component (test structure, or experimental substructure) and a numerical model (analytical substructure). During the test, the displacement response of the structure is calculated from the integration of the equations of motion. The displacements are simultaneously imposed to the test structure using hydraulic actuators and to the analytical substructure. The corresponding restoring forces developed by the test

b. Structure Congress 2007.doc

Figure 6.6 Files for Publications

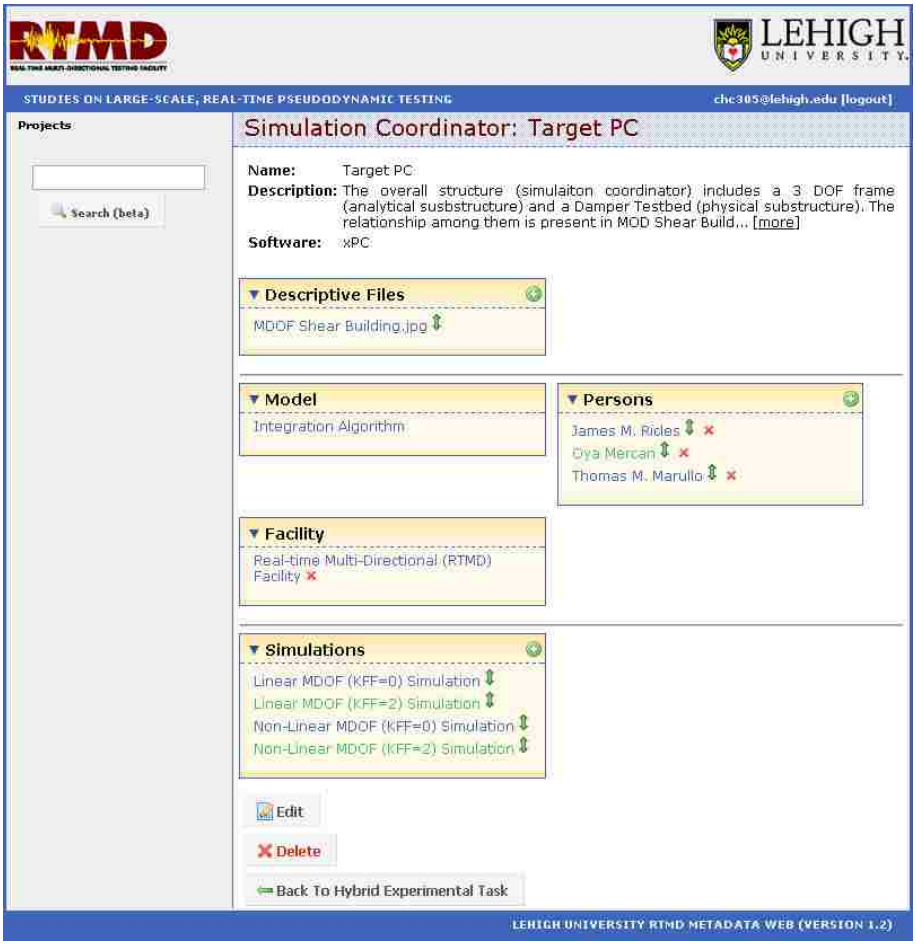


Figure 6.7 Target PC Web Page

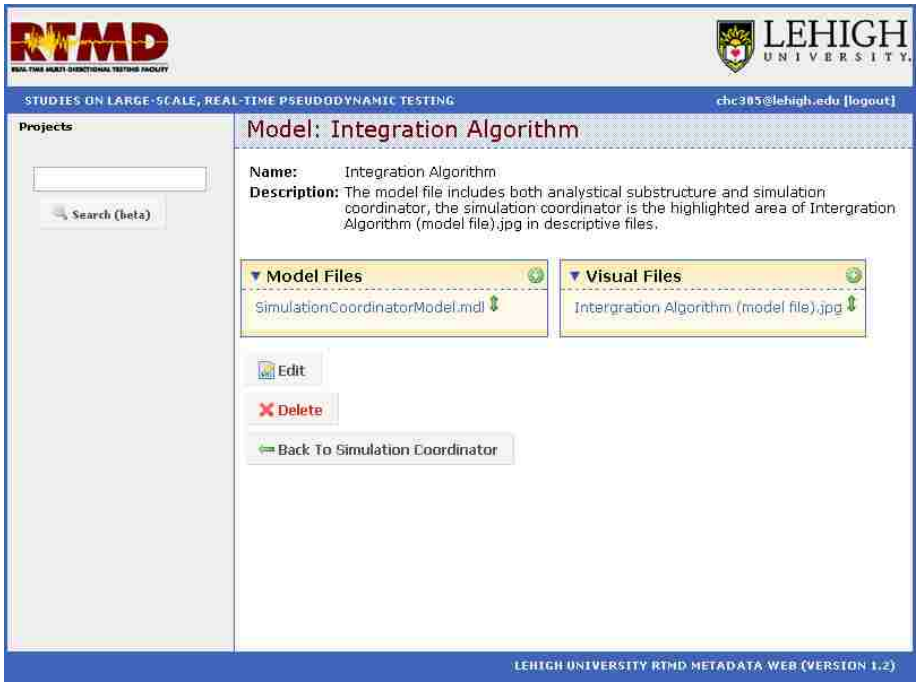


Figure 6.8 Integration Algorithm Web Page

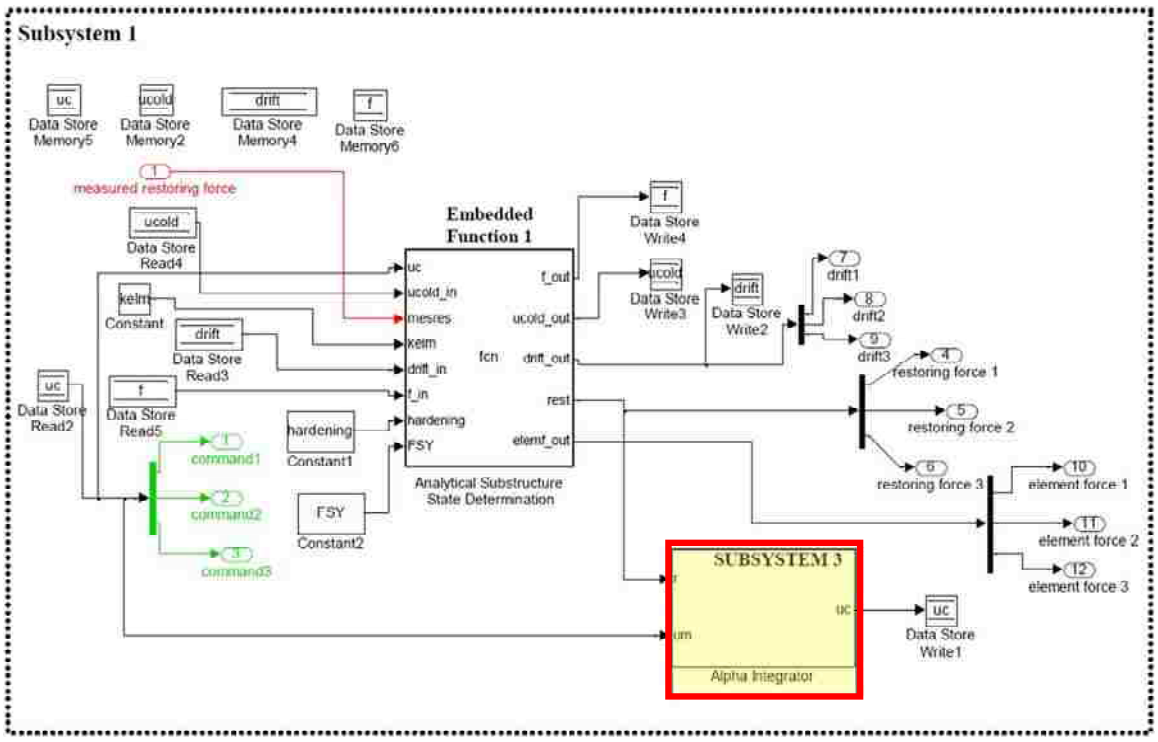


Figure 6.9 Subsystem 1 of Simulink Model for Real-Time Hybrid PSD Simulation – Simulation Coordinator in Highlighted Box

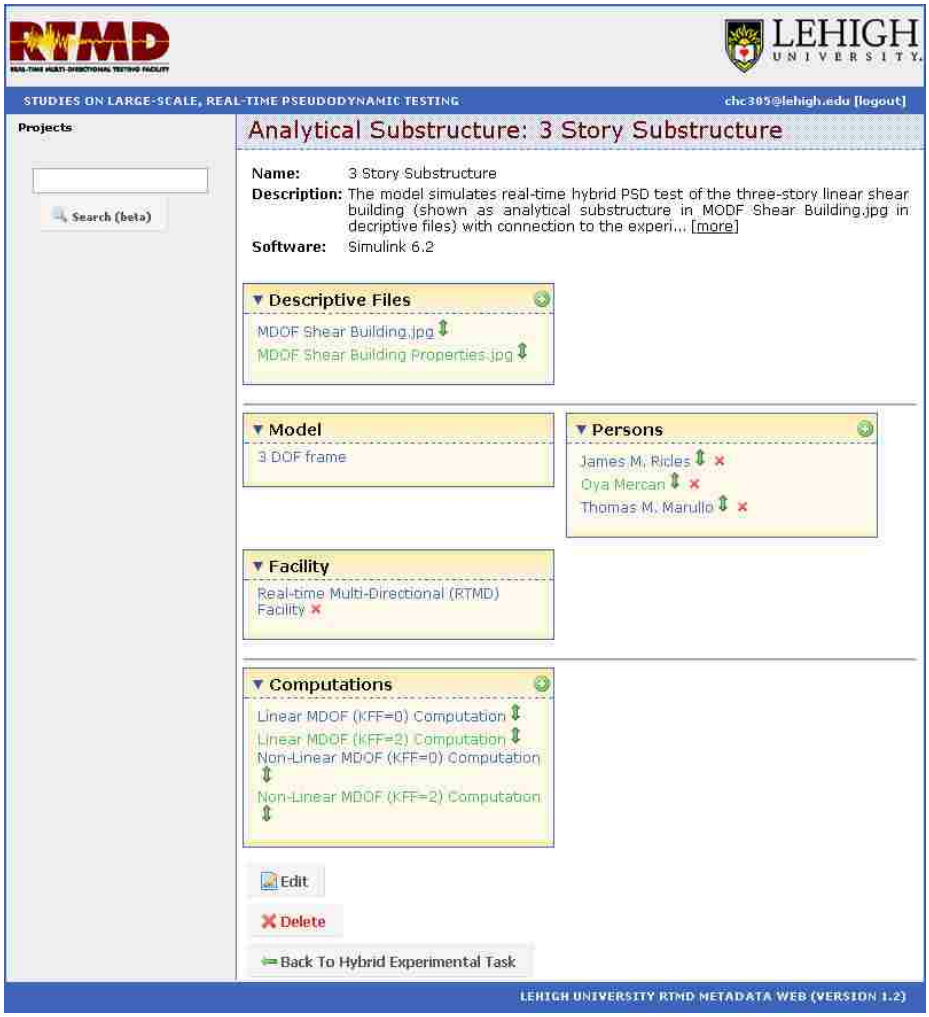


Figure 6.10 3 Story Substructure Web Page

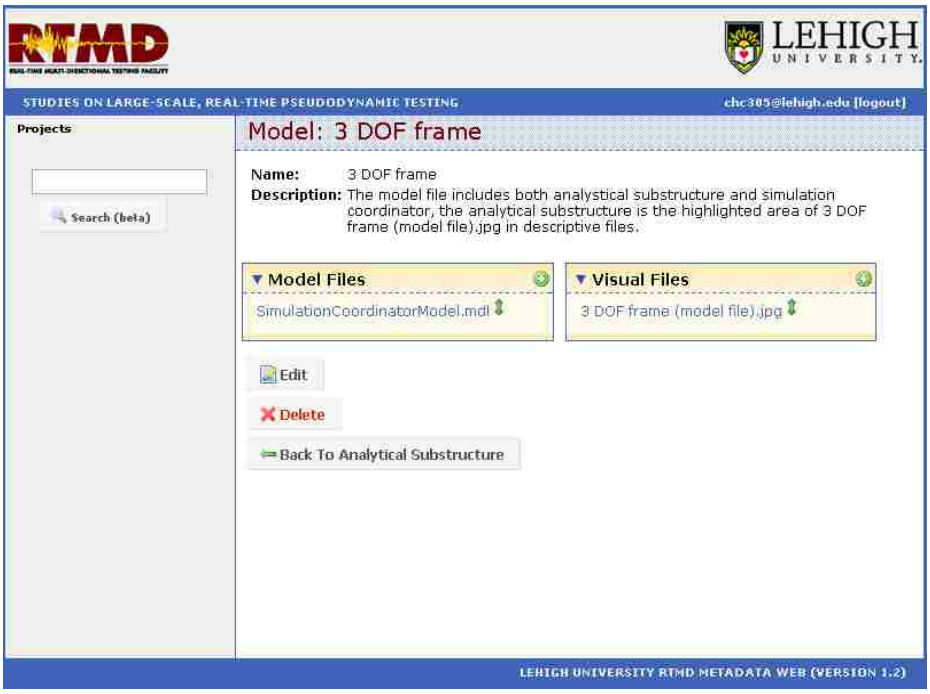


Figure 6.11 3 DOF Frame Web Page

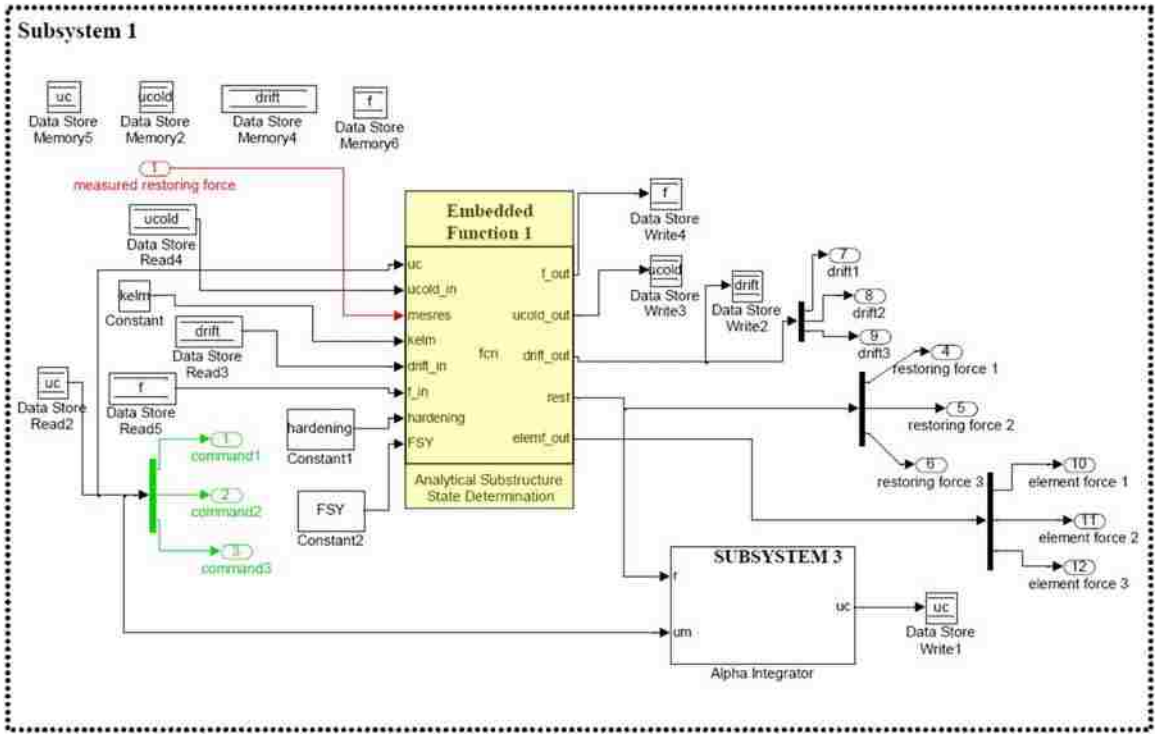


Figure 6.12 Subsystem 1 of Simulink Model for Real-Time Hybrid PSD Simulation – 3 DOF Frame Analytical Substructure in Highlighted Box

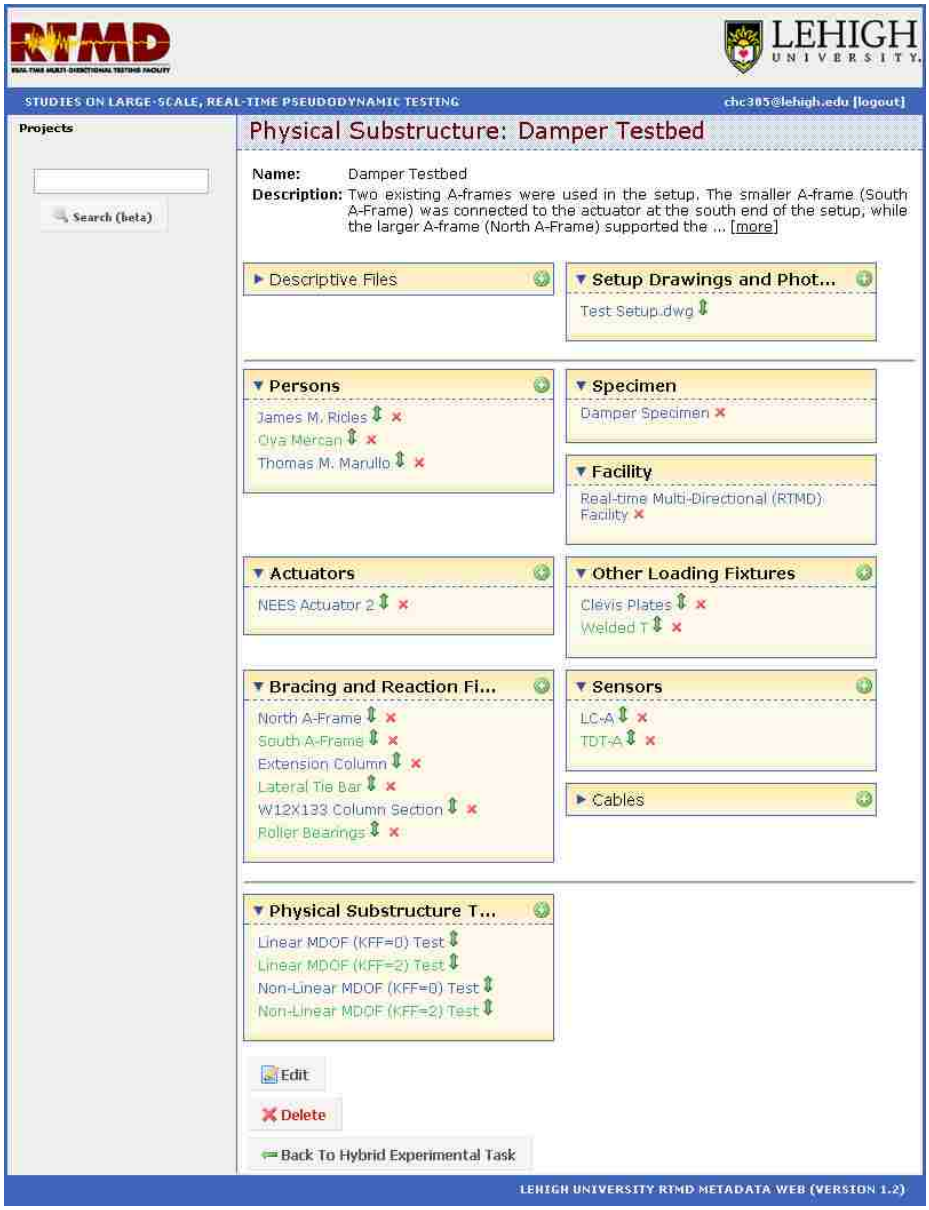


Figure 6.13 Damper Testbed Web Page

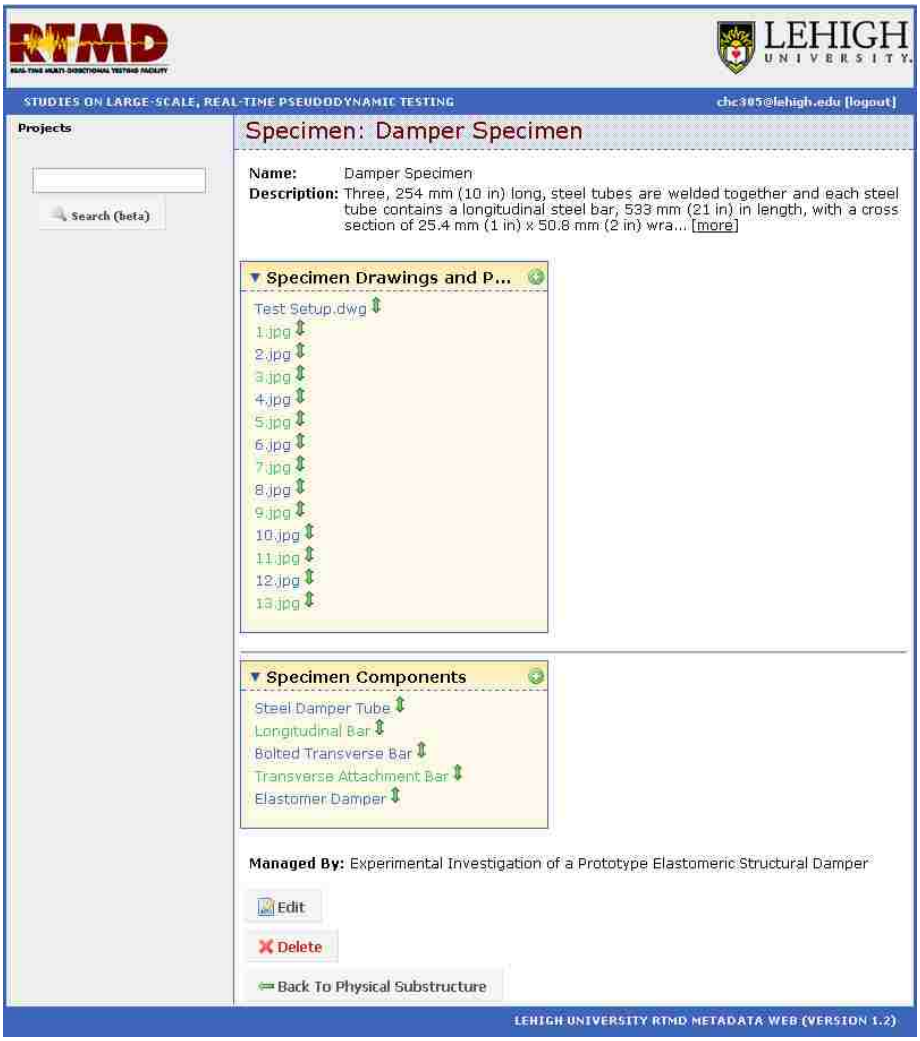


Figure 6.14 Damper Specimen Web Page

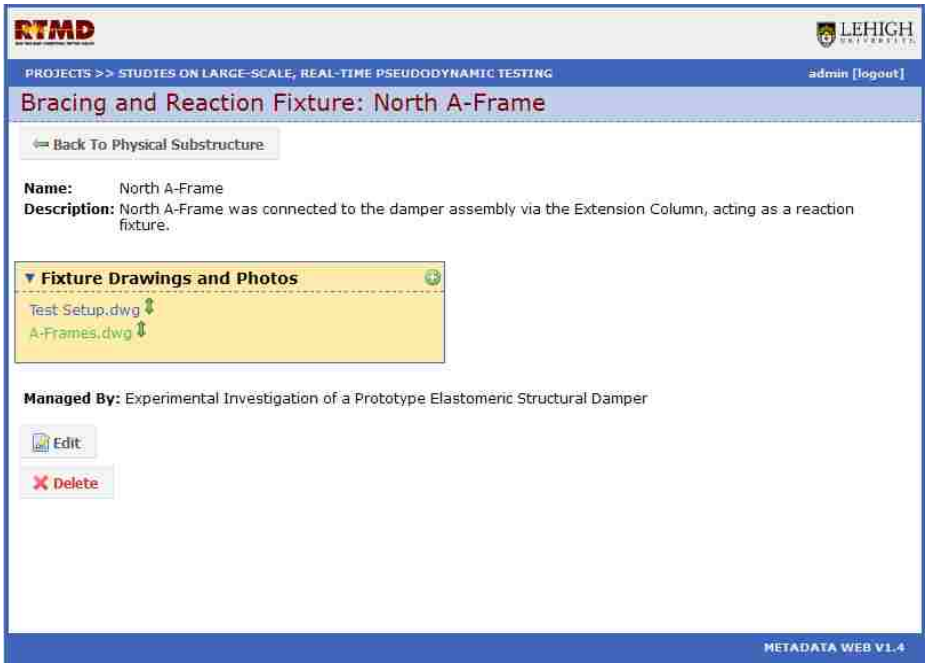


Figure 6.15 North A-Frame Web Page

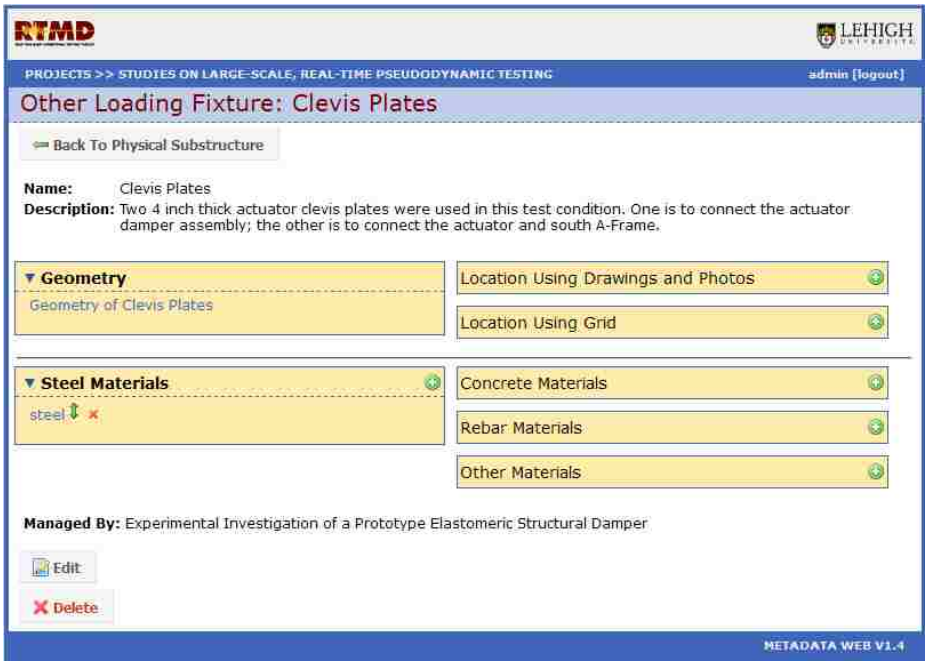


Figure 6.16 Clevis Plates Web Pages

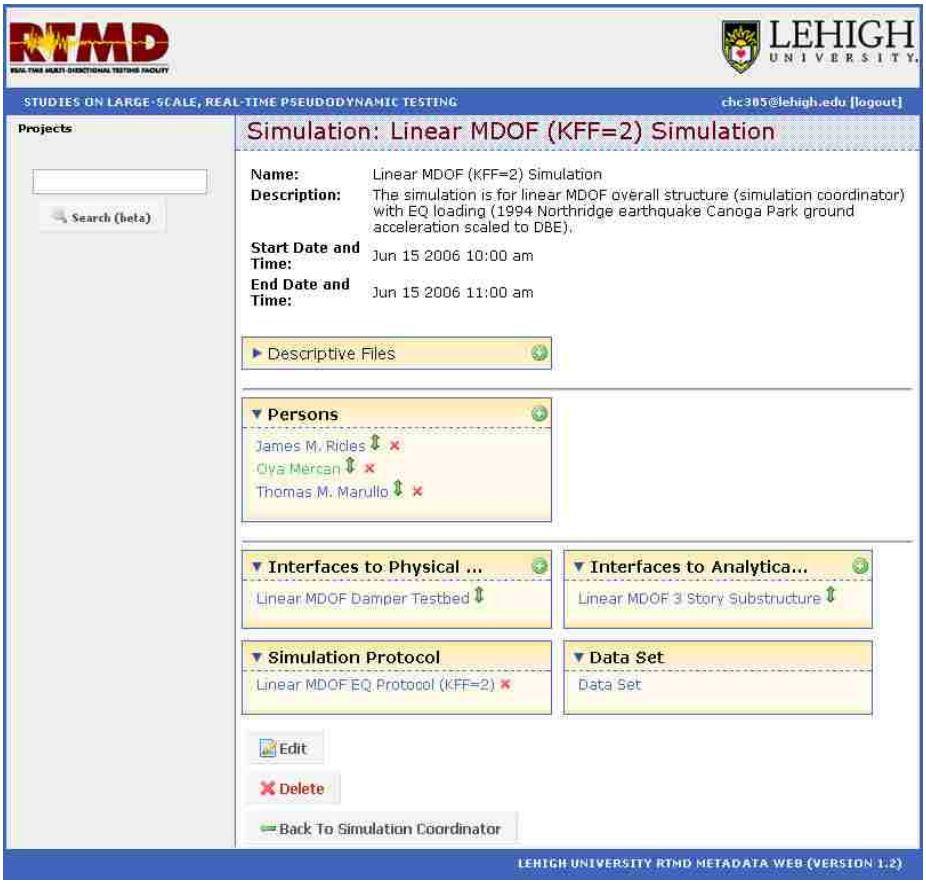


Figure 6.17 Linear MDOF (KFF=2) Simulation Web Page

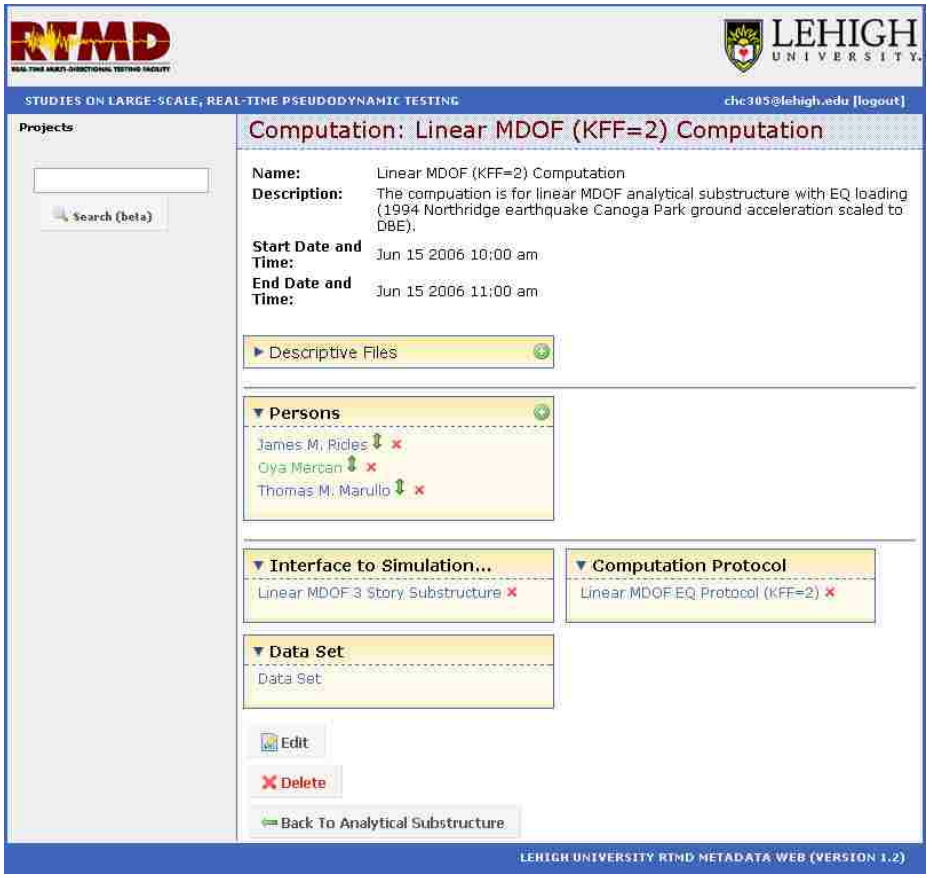


Figure 6.18 Linear MDOF (KFF=2) Computation Web Page

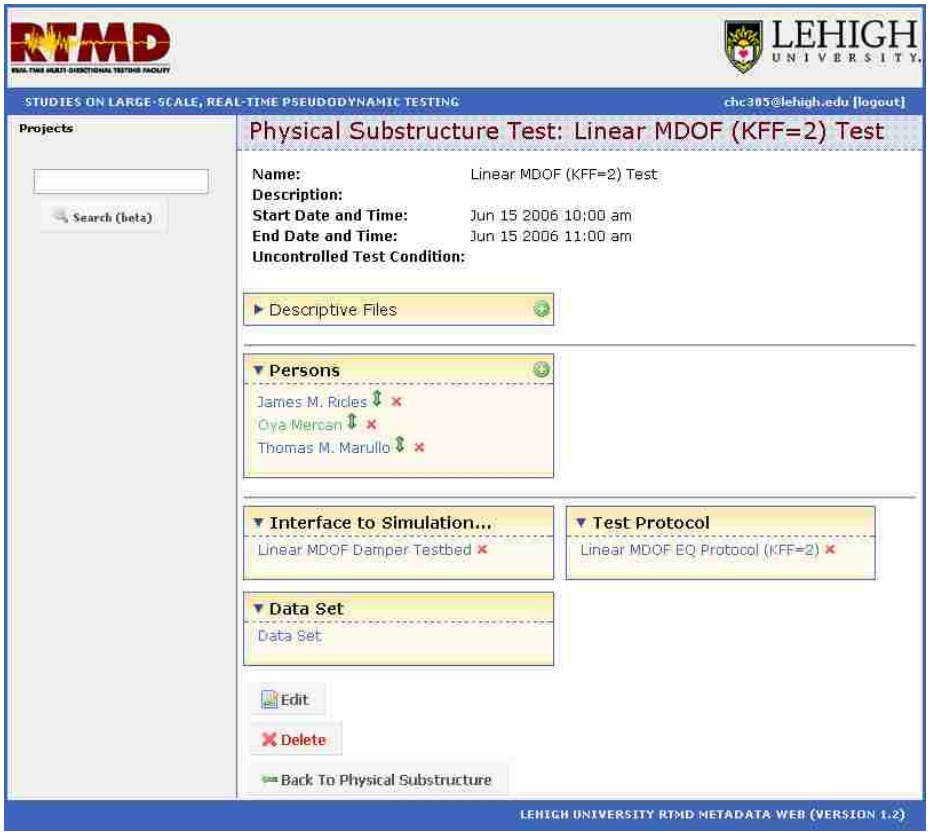


Figure 6.19 Linear MDOF (KFF=2) Test Web Page

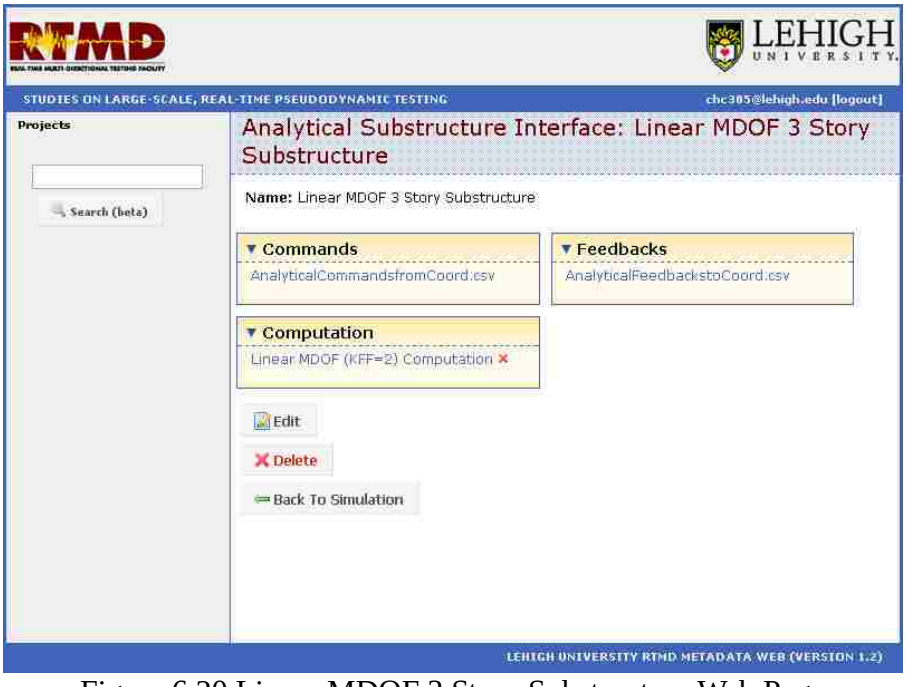


Figure 6.20 Linear MDOF 3 Story Substructure Web Page

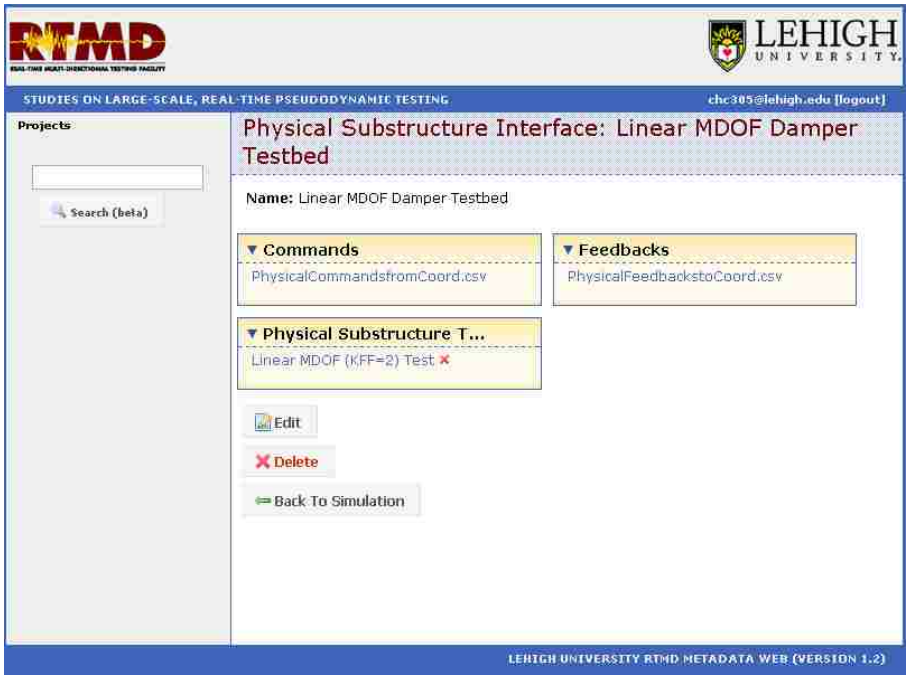


Figure 6.21 Linear MDOF Damper Testbed Web Page

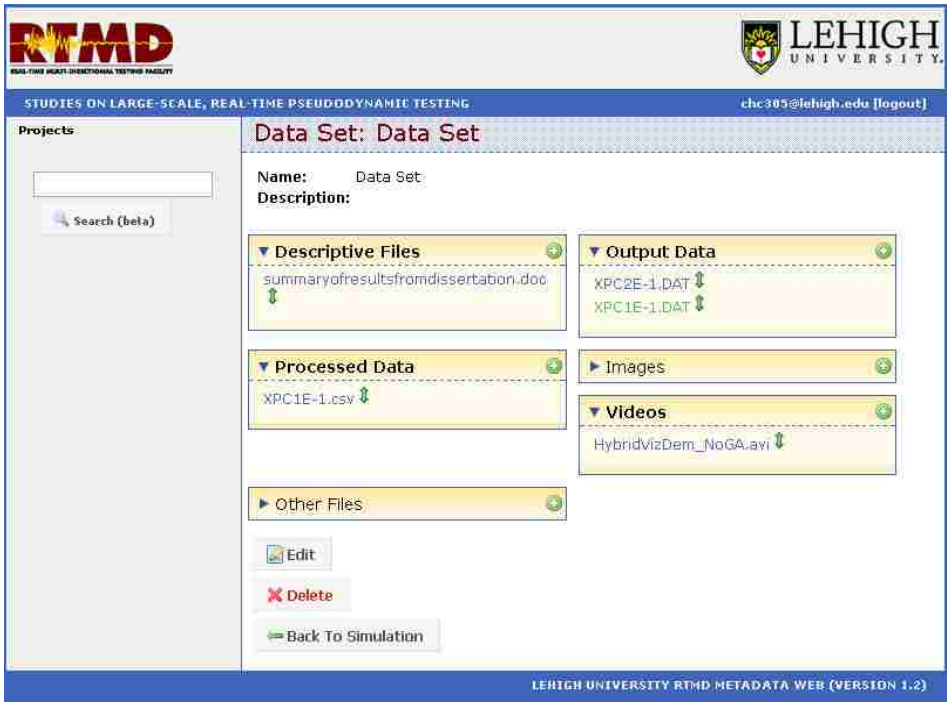


Figure 6.22 Data Set Web Page for Simulation

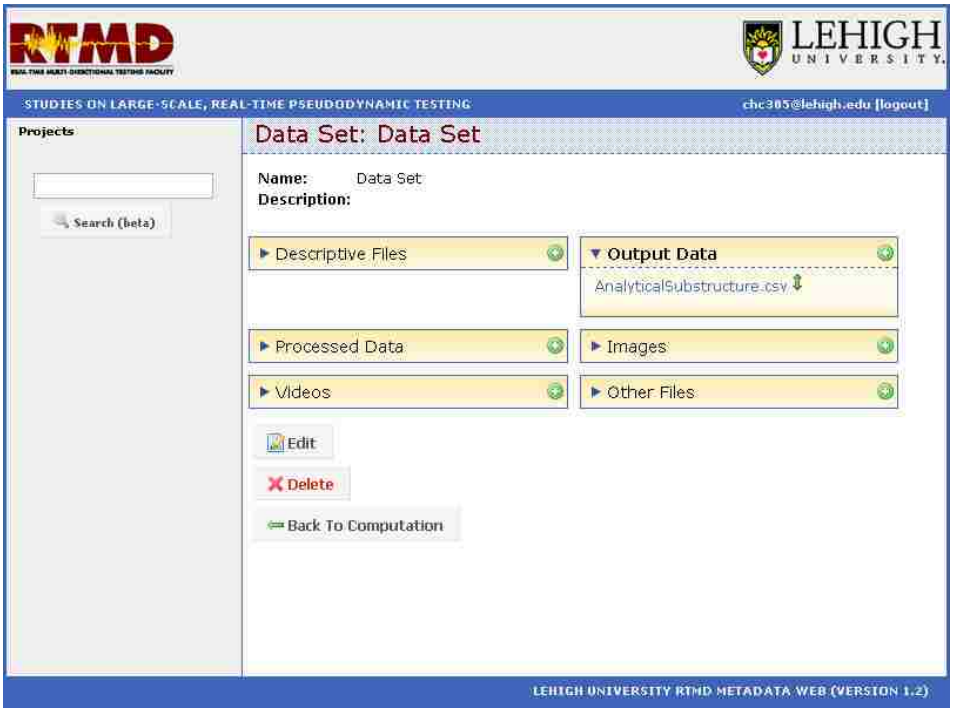


Figure 6.23 Data Set Web Page for Computation

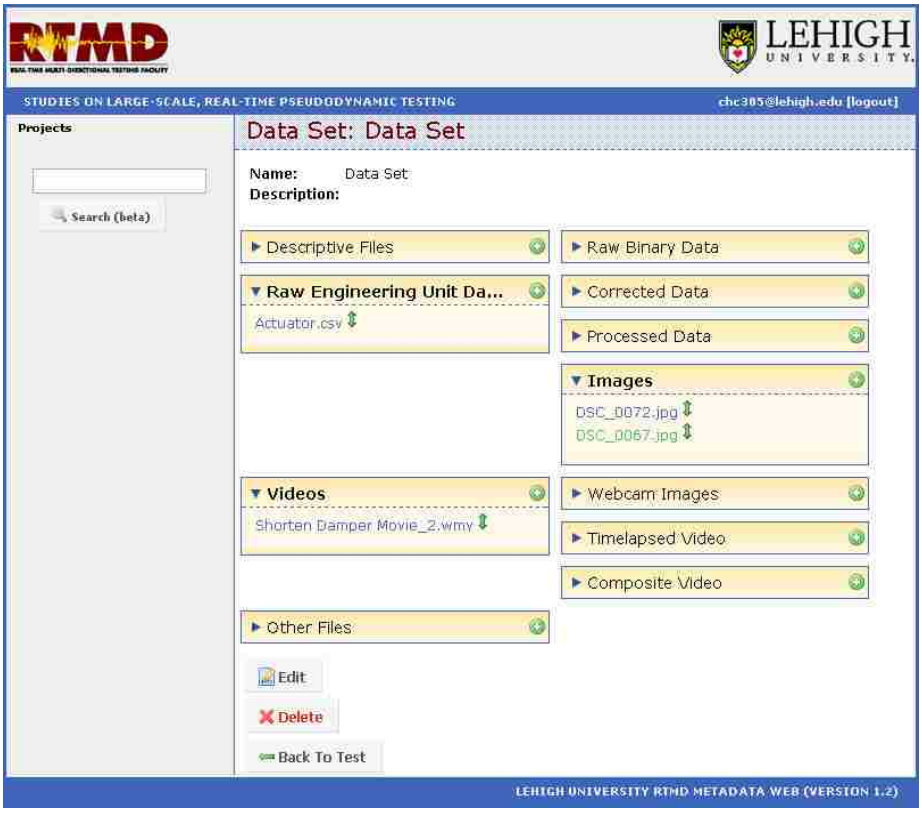


Figure 6.24 Data Set Web Page for Physical Test

Chapter 7

Summary, Conclusions, and Future Work

7.1 Summary

This research further advanced the Lehigh Model, which was developed previously by Lee et al. (2006), and presented an implementation of the Lehigh Model, the Lehigh RTMD Metadata Web, developed by Marullo (2007). The presentation of the Lehigh RTMD Metadata Web showed how it was developed from the updated Lehigh Model.

The Lehigh Model is a data model for large-scale structural experiments, which was developed at the Real-Time Multi-Directional (RTMD) earthquake simulation facility in the ATLSS Center. The development of the Lehigh Model was based on a review of previous work on data models and databases for structural tests, and a study of large-scale structural experiments conducted at the RTMD earthquake simulation facility. Some of the classes and attributes of the Lehigh Model were updated in this thesis based on further studies of large-scale structural experiments and analytical studies.

A web application, named the Lehigh RTMD Metadata Web, was developed by Marullo (2007) to implement the Lehigh Model. This web application enables users to access and retrieve information and data through the internet. Two examples of applying the Lehigh RTMD Metadata Web were presented in this thesis. First, the Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems Project is an example involving a typical

experiment. Second, the Studies on Large-scale, Real-time Pseudodynamic (PSD) Testing Project is an example involving hybrid simulations.

7.2 Conclusions

The Lehigh Model has been successfully developed to represent the information and data associated with large-scale structural experiments. The updated classes and attributes of the Lehigh Model have improved the representation of this information and data. The Lehigh RTMD Metadata Web was developed to implement the Lehigh Model. The two examples given in this thesis show how the Lehigh RTMD Metadata Web can be used to organize the information and data related to structural experiments. In addition, the examples show how users can access and retrieve the information and data.

7.3 Recommendations for Future Work

Future work on the Lehigh Model should focus on developing classes and attributes for other large-scale structural test methods, such as Tsunami wave tank experiments, shaking table experiments, and centrifuge experiments.

Future work on the Lehigh RTMD Metadata Web should focus on updating the web application as the Lehigh Model is improved, and on developing a search tool to help users to quickly find specific information and data.

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Vita

Stanley C.H. King was born on November 4, 1979 in Taipei, Taiwan, R.O.C.. He is son of Nan Chan Ching and Li-Wa King-Huang. Stanley received his Bachelor of Science degree in Civil Engineering at Tamkang University, Tamsui, Taiwan, R.O.C. in June 2002. He then went to U.S to pursue his Master of Science degree in Civil Engineering at Lehigh University, Bethlehem, Pensonsylvania. He will receive his degree in May 2011. He is working as a structural engineer in Goldstein Associations in New York City in the past 3 years and will be continuously working over there.