Nonrectangular concrete walls under multi-directional loads – analytical simulation and remote participation in experimental research

Sri Sritharan, Jian Zhao, Jonathan Waugh & Manimaran Govindarasu
Iowa State University, Ames
Iowa, USA

ABSTRACT: This paper summarizes the progress of research made on two aspects of a PreNEESR project that investigates behavior of nonrectangular concrete walls subjected to multi-directional loads. First, using the past test data, the fiber-based analytical modeling of concrete walls is examined. Second, several challenges of remote participation in experimental research are discussed, with an introduction of a real-time data visualization tool (RVtool) that is designed to enhance collaboration among the researchers.

Keywords: Nonrectangular walls, concrete, seismic, multi-directional load, remote participation

1 INTRODUCTION

Researchers from the University of Minnesota (UMN), Iowa State University (ISU), and University of Puerto Rico at Mayagüez and a consulting structural engineer from the Nakaki Bashaw Group, Inc. in California have undertaken a collaborative PreNEESR project with financial support from the National Science Foundation (NSF). The project focuses on experimental and analytical efforts to investigate seismic behavior of nonrectangular (or flanged) structural walls subjected to multi-directional loading. The experimental component of the study will utilize the NEES Multi-Axial Subassemblage Testing (MAST) system at UMN. The analytical study to date has focused on developing reliable models suitable for simulating behavior of nonrectangular walls under multi-directional loads using an open source finite element package (OpenSees – [1]) and existing test data. To compare the analysis results with experimental data in real time during testing of the large-scale walls, a web-based data visualization tool has been developed for the MAST system. This tool is also introduced in this paper with description of its capabilities and how it will facilitate participation of various researchers, especially those at remote locations, during testing of large-scale walls planned as part of the project.

2 PAST RESEARCH

Seismic behavior of nonrectangular concrete walls has been investigated through limited experimental and analytical studies. These studies include testing of I shaped walls by Oesterle et al. in 1979, C-walls by Sittipunt and Wood in 1992, and T-walls by Thomsen and Wallace in 1995. Furthermore, all of these studies have focused on understanding the wall behavior under lateral loads applied in the web direction.

Oesterle et al. tested two I-walls during their investigation on lateral load behavior of several structural walls in 1979. The investigators concluded that the large out-of-plane stiffness of the flange prevents global instability of the boundary elements. However, the large flexural capacities of the I-walls require that the walls be designed to resist high shear stresses. The experimental results showed ductile hysteric behavior and behavior with no evidence of any pinching effects even when shear stresses exceeded $7\sqrt{f_c'}$.

Sittipunt and Wood tested two C-walls as part of their research to develop analytical models that can characterize the inelastic hysteretic behavior of reinforced concrete structural walls. Each wall had two 36 in. webs and a 60 in. flange connecting the webs. The walls were 9 ft tall and 3 in. thick. The walls were modeled using plane stress concrete elements and two node link elements to represent the reinforcement. The concrete elements used the smeard crack concept with fixed orthogonal cracks. The concrete elements modeled two functions: the stress function representing the stress-strain (shape?) relationship normal to the crack and the shear stress function representing the linear? stress-strain relationship parallel to the base of the wall. The stress-strain relationship of the reinforcing steel was modeled using the Ramsberg-Osgood equation. The wall lateral deformation resulting from strain penetration effects, as described in the next section, was not included. However, the analytical model accurately captured the response of the two test walls. After confirming the accuracy of the analytical models using test data, Sittipunt and Wood conducted a parametric study to determine the effect of flange size and reinforcement details as well as openings on the lateral load behavior of walls. The researchers concluded that the effective flange width for C-walls can be larger than the effective flange width provisions specified for T-beams in the 1989 ACI Building Code (How does this compare to the 02 code?). When the flange is in tension, using a smaller effective flange width can underestimate the wall's flexural strength, which can lead to insufficient shear reinforcement and brittle failure of the wall.

The study most directly related to that current investigation is the testing of two T-walls by Thomsen and Wallace (1995). The first T-wall was created by using the details of two intersecting rectangular walls. The researchers wanted to know the effect of not giving consideration to the unique features of the T-wall. The first wall (TW1) performed poorly because of the small confined concrete region in the stem. The transverse steel was not spaced closely enough to prevent brittle buckling of the web. The second T-wall (TW2) was designed based on a displacement based design procedure developed by the researchers. TW2 had a much larger confined concrete region at the stem tip, and the stirrups were spaced closely to prevent the buckling failure in TW1.The cross section of TW2 is shown in Figure 1, and the lateral force-displacement of this wall may be seen in Figure ?. Thomsen and Wallace found that when the flange was in compression, both the compressive strains and depth of the neutral axis were small. Additionally, the wall was very ductile and the longitudinal tension reinforcement developed high strains in this loading direction. When the loading direction was reversed and the flange was placed in tension, the ductility was decreased, but the lateral flexural strength increased. When the flange was in tension, the stiffness gradually decreased starting from a low lateral drift of 0.35% rather than an abrupt change in stiffness observed for the flange in compression direction loading. Overall, the wall showed good hysteretic response with insignificant pinching of the loops in both loading directions.

3 SIMULATION OF WALL BEHAVIOR

Simulation of nonlinear response of rectangular and nonrectangular concrete walls has been attempted through various analytical models. These models have used simple beam-column elements to fiber-based beam-column elements to plane stress elements to solid elements. There are benefits and challenges associated with application of each of these elements to modeling concrete walls. However, the accuracy of the analytical simulation will depend on how accurately various components of the wall response are captured with minimal compensation of error. When different components contribute to the total lateral load response of walls, the error compensation may occur by underestimating the contribution of one component while overestimating the contribution of another component. Such error compensation may lead to satisfactory prediction of force-displacement responses; however, it will introduce significant error in the prediction of localized damage as well as strains and stresses in the critical regions (Sritharan et al. 2000).

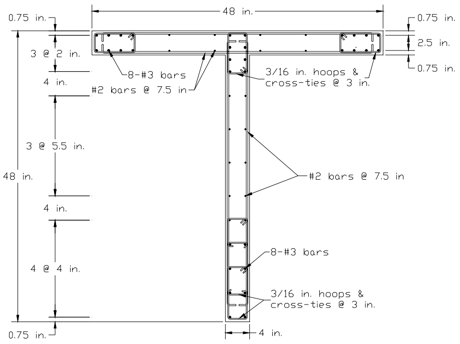

Figure 1. Cross section of TW2 tested by Thomsen and Wallace.

Under lateral loads, the response of well-designed walls will be influenced by flexural and shear components. With a large aspect ratio (i.e., the ratio of height to length), the flexural component will be dominant in the wall response; some contribution of the shear deformation should also be expected. Several factors will dictate the flexural response of the wall. Listed below are various issues that need attention for accurately modeling the global and local response of well-designed, flexure dominant, nonrectangular concrete walls under lateral loads:

- *Material behavior:* Depending on the element type used, nonlinear behavior of concrete and steel or their effects on section or member behavior should be accurately modeled; suitable hysteretic rules for the nonlinear response of materials should be either adopted or reflected in the response at the section or member level.

- *Strain penetration effects:* Due to flexural action, significant strains develop in the longitudinal reinforcement at the wall base. These steel strains penetrate into the footing along the fully anchored longitudinal reinforcing bars, causing slip of these bars over the top portion of the anchorage length and thus the rotation of the flexural member at the wall-to-foundation intersection. Unless this flexural rotation is carefully modeled, the strains and stresses in the concrete and steel reinforcement in the critical region, section curvature, and effective elastic stiffness and lateral deformation of the wall will not accurately modeled by the finite element model. Ignoring the penetration effects can produce satisfactory force-displacement response, but with significant error in the localized strains and curvature (Sritharan et al. 2000; Zhao and Sritharan 2005)

- *Shear lag effects:* In flanged walls, the phenomenon known as shear lag influences the bending stress distribution in flanges and thus the length of the flanges that will effectively participate in resisting the lateral load. The shear lag effects on flanged walls are pronounced when flanges are subjected flexural tension. If the shear lag effects are ignored, the wall resistance as well as strains and stresses in the critical region will be inaccurately estimated by the finite element model.

- *Axial load effects:* Structural walls that are designed to resist lateral forces can be subjected to significant gravity loads. These axial loads in combination with the lateral displacement can induce additional overturning moments. Alternatively this moment can be viewed as that causing additional lateral displacement of the wall. This phenomenon is known as the P-Δ effects, which should be accurately accounted for in the analysis. Depending on the loading direction, the resultant gravity load is unlikely to be acting at the neutral axis depth of the cracked section of the wall. Therefore, the moment induced by the gravity load times the distance from the location of the resultant gravity force to the neutral axis should also be given consideration in the analysis.

- *Shear deformation:* Flexure dominant flanged walls can be subjected to large shear forces especially when the flange of the wall is in tension. Beyond developing diagonal cracks in the web, these walls can undergo large shear deformation under lateral loads. Hence, ignoring the shear deformation in the lateral load analysis of walls will underestimate lateral deflection and overestimate the effective stiffness of the wall.

- *Flexure-shear interaction:* In the plastic hinge regions, a significant portion of the lateral load may be carried by truss action after developing diagonal cracks in the web of the wall (Park and Paulay 1975), which will impose additional demand on the vertical longitudinal reinforcement. The interaction between flexural and shear actions represented by the truss action may be pronounced at large lateral displacements and will influence the distribution of the flexural strains in the concrete and steel reinforcement as well as the lateral deformation of the wall. Unless this interaction is accountant for, the concrete and steel strains and the lateral displacement of the wall will be underestimated by the analysis model while overestimating the flexural capacity of the wall.

In addition to the above discussed issues, the response of inadequately designed walls may be influenced by bond failure of lap splice or anchorage failure of reinforcement and/or shear failure caused by yielding of shear reinforcement, web crushing or sliding at the base (Paulay and Priestley 1996).

4 FIBER-BASED ANALYSIS

To date, the analytical effort in the PreNEESR project has mainly focused on modeling lateral load response of concrete walls using the nonlinear fiber-based beam-column element available in OpenSees [?]. In the fiber-based analysis method, the flexural member is represented by unidirectional steel and concrete fibers, making the description of the corresponding material models relatively easy. Because the steel and concrete fiber responses are specified in the direction of the member length, the fiber analysis concept is suitable for modeling flexural members regardless of the cross-sectional shape or the direction of the lateral load.

The fiber analysis typically follows the direct stiffness method, in which solving the equilibrium equation of the overall system yields the nodal displacements (Spacone et al. 199a, 199b). After the element displacements are extracted from the nodal displacements, the element forces are determined and the member stiffness is upgraded, based on which the global stiffness matrix is assembled for the next time step. The stiffness and forces of the fiber-based elements are obtained by numerically integrating the section stiffness and forces corresponding to a section deformation (i.e., axial strain $\bar{\varepsilon}$ and curvature ϕ).

The section deformation is calculated through interpolating the element end deformations (i.e., displacement and rotation) at the integration points. From the section deformation, the strain in each fiber (ε) is obtained using the plane sections remain plane assumption. For example, the fiber strain is calculated using, $\varepsilon = \bar{\varepsilon} + \phi y$, where y is the distance of the fiber from the centroid of the section. The fiber stress and stiffness are updated according to the material models, followed by upgrading of the section force resultant and the corresponding stiffness. The neutral axis position of the section at an integration point is determined through an iterative procedure, which balances the force resultants at the section level as well as at the member level.

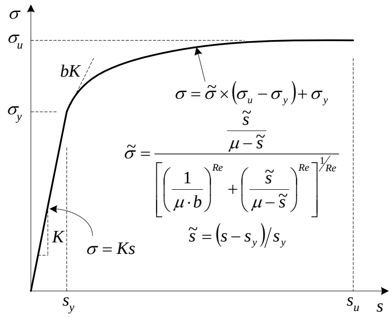

Figure ?. The proposed bar stress vs. loaded end slip for fully anchored reinforcing bars into footings.

Although flexure-shear interaction is not typically integrated in the element formulation and the built-in plane section assumption may not be appropriate for modeling response of some flexural members and response of shear-dominant members, fiber analysis remains the most economic and accurate means to capture seismic behavior of concrete structures (Spacone et al. 1996a, 1996b). In addition, if the member end rotation due to bond slip resulting from strain penetration effects is accurately modeled, the fiber analysis has the potential to satisfactorily capture localized structural responses such as bar strains and section curvature.

4.1 *Zero-Length Bond-Slip Element*

To capture the strain penetration effects under multi-directional load, the slip that occurs to the longitudinal reinforcing bars at the wall base should be modeled on an individual basis. Using the zero-length section element available in OpenSees, a bond slip model to capture the strain penetration effects has been recently introduced (Zhao and Sritharan 2005). In this element, the bar stress vs. the slip response at the end of the flexural member is characterized using the stress vs. slip function shown in Fig. ? with a hysteresis rule presented in Fig. ?. In this approach, the slip when the bar stress reaches the yield and ultimate strengths are obtained from:

$$s_y = 0.4\left(\frac{d_b}{4}\frac{f_y}{\sqrt{f_c'}}(2\alpha + 1)\right)^{1/\alpha} + 0.34 \qquad (1)$$

$$s_u = 35 s_y \qquad (2)$$

where d_b = bar diameter; f_y = yield strength of bar; f'_c= concrete strength of footing; and α = exponent parameter.

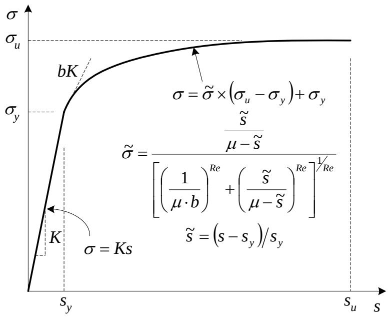

Figure ?. The proposed bar stress vs. loaded end slip for fully anchored reinforcing bars into footings.

4.2 *Summary of Findings*

Presented in this section is a summary of findings from fiber-based analysis of TW2 (i.e., second of the two T-walls tested by Thomsen and Wallace) and RW2 (i.e., the second of two rectangular walls tested by Thomsen and Wallace). Both RW2 and TW2 were modeled using nonlinear beam-column elements with existing material model for concrete and steel reinforcement fibers. The zero-length bond slip element described above was used to capture the strain penetration effects; the shear deformation of the wall was, however, not modeled. The analysis was conducted in the web direction of the wall under monotonic and cyclic lateral loading.

- Strain penetration is important in simulating the response of reinforced concrete walls.
- The force-displacement response for RW2 is shown in Figure ?. The part of the differences between the OpenSees and experimental response is due to the inadequacies of the material models that are currently available in OpenSees.
- The force-displacement comparison for TW2 shown in Figure ? shows that when the flange is in compression, positive displacement, the fiber model matches the experimental results accurately. However, when the flange is in tension, negative displacement, the model over predicts both the strength and stiffness of the wall. This is due to the shear lag effect. Shear lag must be included in the modeling of nonrectangular walls. The material model inadequacies found in the response of RW2 are also present in the response of TW2.

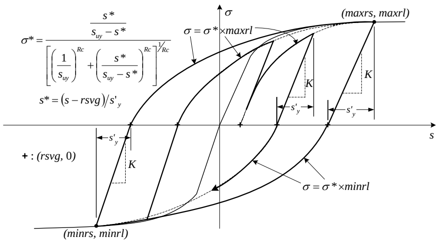

Figure ?. Hysteric rule proposed for the bar stress vs. loaded end slip of fully anchored bars into footings.

5 REMOTE PARTICIPATION

The NEESgrid system (NEESit 2005) offers a variety of tools for collaboration, telepresence, simulation, and local data management, which enable researchers to plan activities, exchange information, store and transmit results, remotely view live video or static images, and remotely control telerobotic cameras. While these tools have been continuously improved with an objective of promoting collaboration among researchers, the NEESgrid capabilities available at the beginning of the PreNEESR project were considered too limited in scope to foster effective collaboration between researchers involved in the project. Presented below are examples of NEESgrid limitations, most of which do still exist:

- Remote users can observe a test at a NEES site through video and real-time data streamed as a function of time, but cannot effectively participate in the decision-making process. This limitation is due to the lack of information available at a remote site on the status of the test specimen and the condition of the equipment, which is controlled locally at the equipment site.
- Real-time sharing of sensor data is now provided using the Ring Buffer Network Bus (RBNB) data turbine technology (Creare 2005). Remote users can view the sensor data through the RBNB plotting tool, which currently provides data only as a function of time. Plotting capabilities to manipulate and visualize data channels (e.g., viewing force-displacement response) are not available. The RBNB technology was not adopted by the NEESgrid at the beginning of the PreNEESR project, and as a result the number of data channels that could

Deleted:

be transmitted to a remote site was once limited to 16.

- Real-time comparisons between experimental data and analysis results are not possible, which is considered critical for the large-scale T-wall tests under multi-directional loads. Real-time comparison of experimental data and analysis results will be needed to confirm suitability of various load protocols immediately before their application during the wall tests. To make this confirmation by researchers at the NEES equipment or remote sites, they will require comparison of results from the completed tests.
- Data visualization tools are not available for both experimental data and OpenSees simulation results. Note that OpensSees has been adopted as a simulation tool in the NEESgrid.

5.1 *Visualization Tool*

To facilitate real-time collaboration among participants of the PreNEESR project, a real-time visualization interface for MAST facility (MAST-RVtool, MAST-RVISU? MAST-RVIS? depicted in Fig. ?), has been developed. The development was partially funded by the ISU's Information Infrastructure Institute (ICube@ISU). The web-based tool obtains numerical data in real time from an RBNB sever and provide visualization of the data of interest. When the data-providing server is not the one connected to the data acquisition system at the equipment site, a data mirror will be created at the server such that the information of interest can be available for the tool. MAST-RVtool allows remote researchers to 1) monitor the condition of its hydraulic actuators (i.e., force and displacement of the actuators) through progress bars and data viewer; 2) set soft limits (i.e., limits used by a remote user for research purposes, and not for actuator control, such as maximum gravity load fluctuation);, 3) monitor the load path effects on the specimen, which helps the determination of critical paths for the future load cycles, and 4) compare the predicted force-displacement responses with measured responses, all in real-time.

Researchers at both remote locations and the equipment site can run the MAST-RVtool at the same time, hence, all research participants can obtain the same information such as the condition of the test unit and equipment. With the real-time comparison between analytical predictions and experimental data, all researchers will be able to contribute effectively in making decisions, such as deciding the load path for the subsequent tests. In addition, the RVtool will foster collaboration between experimental and theoretical researchers. For example, if discrepancies are found between the predicted results and experimental data, the theoretical researchers can update the models and parameters for the analysis based on the available testing data to revise the predictions before continuing the test, recommend appropriate changes to the test protocol that may assist with comprehending the difference between the experimental and theoretical results, and request any additional data measurements that may be feasible and necessary to improve the analytical model.

Deleted: In this process,

Deleted: is expected to

Deleted: Furthermore

Deleted: there are

Deleted: comparison of results in real-time will allow

Deleted: to revise

Deleted: ir

Deleted: with remainder of a

Deleted: Upon realizing the limited capabilities of NEESgrid for real-time collaboration in the PreNEESR project, a visualization tool

Deleted: for the NEES-MAST system,

Deleted: which will be refereed to it as MAST-RVtool to represent MAST real-time visualization tool. P

Deleted:),

Deleted: on the MAST system

Deleted: soft limit:

Formatted: Font: Not Italic

Deleted: a

Formatted: Font: Not Italic

Deleted: exceeding a soft limit will not shut the hydraulic system of MAST system)

Deleted: monitor the condition of its hydraulic actuators through progress bars (Fig. ?) and examining the current force and displacement of the actuators (Fig. ?),

Deleted: visualize

Deleted: T-walls

Deleted: and

Deleted: e

Deleted: the

Deleted: next

Deleted: experimental data

Deleted: The MAST-RVtool obtains data from an RBNB sever located either at the MAST facility or at a remote location; the server at a remote location should be configured to mirror the ... [1]

Deleted: various

Deleted: simultaneously

Deleted: ,

Deleted: examine how selected ... [2]

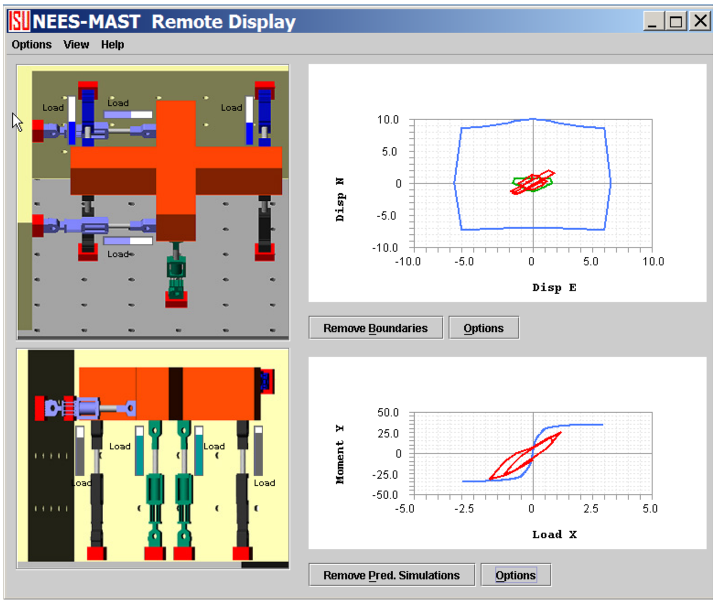

Figure ?. Real-time visualization tool (RVtool) developed for the NEES-MAST system.

6 CONCLUDING REMARKS

A summary of progress made by the writers of this paper in a PreNEESR project that investigates behavior of nonrectangular concrete walls under multi-directional loads is presented. The research efforts have focused on nonlinear fiber-based analysis of concrete walls and development of a real-time visualization tool for the NEES-MAST facility that will enhance collaboration between the experimental and theoretical researchers in the project.

The nonlinear analysis of walls have identified some needed improvements of the existing concrete and steel models, highlighted the benefits of modeling strain penetration effects and how the modeling of the penetration will improve prediction of the local response parameters, and underscored the impact of the plane section remain plane assumption built into the fiber-based concept on the response of flanged walls. Elimination of any potential error compensation in the analysis of concrete walls will be important to ensure satisfactory response of both global and local response of the walls. The strain penetration that occurs along the longitudinal bars into the footing causes the bars to experience slip over a portion of the anchorage length and end rotation of the wall at the wall-to-footing interface. A relationship between the bar stress at the interface and the corresponding slip has been proposed, which will be verified during testing of the walls. The proposed bond-slip model has been incorporated into the fiber based analysis using a zero-length section element.

Although several tools are available for real-time collaboration of research through NEESgrid, it was realized that a real-time visualization tool with specific features will enhance collaboration between the experimental researchers, theoretical researchers and practicing engineer involved in the project. Subsequently, a real-time visualization tool was developed for the NEES-MAST system that will provide conditions of the test unit and status of the hydraulic actuators of the MAST system and compare key experimental and analytical results. Because this information will be available in graphical form to all researchers in real time, it is expected that this tool will involve remote participants in making critical decisions during seismic testing of the large-scale T-walls.

ACKNOWLEDGEMENTS

The study reported in this paper is based upon work supported by the National Science Foundation (NSF) under Grant No. CMS-0324559. The authors gratefully acknowledge the support of Dr. Steven McCabe, who serves as the program director for this grant. The authors also acknowledge ICube at Iowa State University for providing partial funding for the development of the MAST visualization tool.

In addition, the authors thank the collaborators of this project, especially Professor Cathy French, Ms. Suzanne Nakaki and Professor Ricardo López for their valuable feedback on the research progress reported in this paper, Mohammad Fraiwan and Tam Chantem for coding of the RVtool, and Paul Hubbard and Drew Daugherty for their assistance with setting an RBNB server at ISU. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of sponsors. Professor Wallace

REFERENCES

NEESit (2005), IT infrastructure for the NEES Collaboratory, http://it.nees.org/software/index.php.

Open System for Earthquake Engineering Simulation (OpenSees) User Manual. http://opensees.berkeley.edu/.

Spacone, E., Filippou, F., and Taucer, F., "Fiber beam-column model for nonlinear analysis of R/C frames. Part I: Formulation," Earthquake Engineering and Structural Dynamics, Vol 25, 1996, pp 711–725.

Spacone, E., Filippou, F., and Taucer, F. "Fiber beam-column model for nonlinear analysis of R/C frames. Part II: Applications," Earthquake Engineering and Structural Dynamics, Vol 25, 1996, pp 727–742.

Park and Paulay 1972.

Paulay and Priestley 1996

Sritharan, S., Priestley, N., and Seible, F. "Nonlinear Finite Element Analyses Of Concrete Bridge Joint Systems Subjected To Seismic Actions," Finite Elements in Analysis and Design. V. 36, 2000, pp. 215-233.

Zhao and Sritharan.

Last name, First name or Initials (ed.) year. *Book title*. City: Publisher.

Last name, First name or Initials year. Title of article. *Title of Journal* (series number if necessary) volume number (issue number if necessary): page numbers.

Page 6: [1] Deleted **Civil & Construction Engineering** **6/22/2005 2:41:00 PM**

The MAST-RVtool obtains data from an RBNB sever located either at the MAST facility or at a remote location; the server at a remote location should be configured to mirror the data server of the MAST facility. Therefore, the r

Page 6: [2] Deleted **Civil & Construction Engineering** **6/22/2005 3:09:00 PM**

examine how selected analytical predictions compare with experimental data, and