Project #: E-20-W26
Cost share #: E-20-376
Rev #: 1
OCA file #: Active
Work type: RES
Document: GRANT
Contract entity: GTRC
CFDA: 47.041
PE #: N/A

Center #: 10/24-6-R8298-0A0
Center shr #: 10/22-1-F8298-0A0
Mod #: ADM. REVISION

Contract#: CMS-9402572
Prime #: OCA

Subprojects #: Y
Main project #: OCA

Project unit: CIVIL ENGR
Unit code: 02.010.116

Project director(s): GOODNO B J
CIVIL ENGR
(404)894-2227

Sponsor/division names: NATL SCIENCE FOUNDATION
Sponsor/division codes: 107

Award period: 941001 to 960930 (performance) 961231 (reports)

Sponsor amount
Contract value New this change Total to date
0.00 120,000.00
Funded 0.00 120,000.00

Cost sharing amount

23,262.00

Does subcontracting plan apply #: N

Title: OPTIMAL HYBRID CONTROL OF BUILDINGS W/NONLINEAR HystERIC CLADDINg CONNECTIO

PROJECT ADMINISTRATION DATA

OCA contact: Jacquelyn L. Bendall 894-4820

Sponsor technical contact Sponsor issuing office
MEHENDRA P. SINGH CHARLES E. OVERCASH
(703)306-1362 (703)306-1218

NATIONAL SCIENCE FOUNDATION NATIONAL SCIENCE FOUNDATION
4201 WILSON BLVD. 4201 WILSON BLVD.
ARLINGTON, VA 22230 ARLINGTON, VA 22230

Security class (U,C,S,TS) : U
ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A
NSF supplemental sheet
Equipment title vests with: Sponsor
GIT X

Administrative comments -
ISSUED TO SET UP A SUBPROJECT UNDER E-16-X50.
GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 01/29/97

Project No. E-20-W26

Center No. 10/24-6-R8298-0A0

Project Director GOODNO B J

School/Lab CIVIL ENGR

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. CMS-9402572

Contract Entity GTRC

Prime Contract No. 

Title OPTIMAL HYBRID CONTROL OF BUILDINGS W/NONLINEAR HYSTERETIC CLADDING CONNE

Effective Completion Date 960930 (Performance) 961231 (Reports)

Closeout Actions Required:  

<table>
<thead>
<tr>
<th>Closeout Actions Required</th>
<th>Y/N</th>
<th>Date Submitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Invoice or Copy of Final Invoice</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>Final Report of Inventions and/or Subcontracts</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>Government Property Inventory &amp; Related Certificate</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>Classified Material Certificate</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>Release and Assignment</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>N</td>
<td></td>
</tr>
</tbody>
</table>

Comments

LETTER OF CREDIT APPLIES. 98A SATISFIES PATENT REPORT.

Subproject Under Main Project No. 

Continues Project No. 

Distribution Required:

<table>
<thead>
<tr>
<th>Distribution Required</th>
<th>Y/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Director</td>
<td>Y</td>
</tr>
<tr>
<td>Administrative Network Representative</td>
<td>Y</td>
</tr>
<tr>
<td>GTRI Accounting/Grants and Contracts</td>
<td>Y</td>
</tr>
<tr>
<td>Procurement/Supply Services</td>
<td>Y</td>
</tr>
<tr>
<td>Research Property Management</td>
<td>Y</td>
</tr>
<tr>
<td>Research Security Services</td>
<td>N</td>
</tr>
<tr>
<td>Reports Coordinator (OCA)</td>
<td>Y</td>
</tr>
<tr>
<td>GTRC</td>
<td>Y</td>
</tr>
<tr>
<td>Project File</td>
<td>Y</td>
</tr>
<tr>
<td>Other</td>
<td>N</td>
</tr>
</tbody>
</table>
ANNUAL NSF GRANT PROGRESS REPORT

NSF Program: Earthquake Hazards Mitigation
NSF Award Number: CMS-9402572

PI Name: Barry J. Goodno
PI Institution: Georgia Tech
PI Address: School of Civil Engng.
Atlanta, GA 30332-0355

Date: 1-8-96

Check if Continued Funding is Requested

Please include the following information:

1. Brief summary of progress to date and work to be performed during the succeeding period;
2. Statement of funds estimated to remain unobligated—if more than 20%—at the end of the period for which NSF currently is providing support (not required for participants in the Federal Demonstration Project);
3. Proposed budget for the ensuing year in the NSF format, only if the original award letter did not indicate specific incremental amounts or if adjustments to a planned increment exceeding the greater of 10% or $10,000 are being requested;
4. Current information about other research support of senior personnel, if changed from the previous submission;
5. Any other significant information pertinent to the type of project supported by NSF or as specified by the terms and conditions of the grant;
6. A statement describing any contribution of the project to the area of education and human-resource development, if changed from any previous submission; and
7. Updated information on animal care and use, Institutional Biohazard Committee and Human Subject Certification, if changed substantially from those originally proposed and approved.

I certify that to the best of my knowledge (1) the statements herein (excluding scientific hypotheses and scientific opinions) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or individuals working under their supervision. I understand that the willful provision of false information or concealing a material fact in this report or any other communication submitted to NSF is a criminal offense (U.S. Code, Title 18, Section 1001.)

P.I. Signature: 

NSF Form 1328 (1/94)
ANNUAL PROJECT REPORT: Year 1 of 2

Optimal Hybrid Control of Buildings
With Nonlinear Hysteretic Cladding Connection Elements

NSF Award Number CMS-9402572

Year 1 of 2: October 1, 1994 to Sept 30, 1995

PI/PD NAME AND ADDRESS

Dr. Barry J. Goodno, Co-PI, PD
School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0355
Tel.: (404)894-2227
FAX (404)894-2283

Dr. James I. Craig, Co-PI
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0150
Tel.: (404)894-3042
FAX (404)894-2760

Dr. Anthony J. Calise, Co-PI
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0150
Tel.: (404)894-7145
FAX (404)894-2760

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org.: Dr. Mahendra Singh and Dr. Shih-Chi Liu, NSF
2. Program Name: Earthquake Hazards Mitigation Biological and Critical Systems
3. Award Dates: Year 1 - October 1, 1994 to September 30, 1995 (not including 3 month report completion period)
4. Institution and Address: Georgia Institute of Technology Atlanta, Georgia 30332-0355
5. Award Number: NSF Grant CMS-9402572
6. Project Title: Optimal Hybrid Control of Buildings with Nonlinear Hysteretic Cladding Connection Elements

Part II - SUMMARY OF ACTIVITIES IN YEAR #1

Summary
Experimental and analytical investigations of hybrid control systems designed to combine
passive damping provided by cladding-structure interaction with robust active control systems will be continued in this second phase of an overall research plan. The present research continues NSF-funded work recently completed by the research team to develop baseline hybrid building control systems. The passive control forces are introduced through hysteretic interaction between heavy architectural cladding and the supporting structure while the active control forces are assumed to be generated by servo-controlled bracing or mass damping systems. The research builds on extensive experience by the team members in study of passive damping systems for seismic control and of robust control theory and application. The research is organized into three primary tasks: (1) development of new low-dimensional controller designs for robust control of building structures; (2) development of hybrid design approaches for optimization of the combined active (control) and passive (cladding) systems; and (3) experimental verification through simple scale model lab testing.

Scope and Objectives

The research is being carried out by an interdisciplinary team of researchers that combines active and practical involvement in earthquake engineering with broad experience in the development and application of robust control theory in the aerospace industry.

The scope of the research program will be to fully explore the potential of hybrid active/passive control systems in controlling the seismic response of buildings. The passive control forces are introduced through hysteretic interaction between heavy architectural cladding and the supporting structure while the active control forces are assumed to be generated by servo-controlled bracing or mass damping systems.

The principal products of the proposed research are expected to be: (a) new approaches to designing low-dimensional controllers in output feedback settings that can be used for robust control of building structures; (b) integrated design methods for active/passive control systems in which the design process concurrently optimizes active and passive subsystem properties; (c) modeling, analysis and synthesis procedures along with representative designs which combine advanced cladding systems with several different active control systems (e.g., active bracing or variable stiffness systems) to form economical hybrid control strategies; (d) development of improved computer models and extension of present software to include consideration of techniques for hybrid control of buildings using architectural cladding; (e) verification of basic hybrid system behavior through scale model lab experiments.

Results to Date

The results to date are perhaps best summarized by the three refereed papers listed below and the four conference presentations that have been prepared by the research team. The analytical research efforts are well documented in these papers. They describe an imaginative design approach for hybrid robust controllers and they document a successful simulation of these controllers in representative buildings. The results demonstrate that it is possible to design such controllers and that the simulation results predict stable and effective performance that significantly reduces seismic response and potential damage to the structure and possible the

NSF Annual Report: CMS-9402572
The experimental effort is progressing as planned with the test facility completed and fully verified. The building scale model has been constructed and tested to characterize its dynamic behavior and the measurement and data analysis techniques have been developed. The active control system has been through a conceptual design stage and on this basis, the necessary control system implementation hardware and software have been acquired. The control element will be a small high performance servohydraulic actuator that is presently available in the lab. The control system has been designed using Simulink/Matlab and will be implemented in a DSP controller manufactured by IMI Inc. The controller implementation in Simulink is automatically converted to C-code which in turn is compiled for the TI TMS320 DSP chip used in the controller. IMI software is used to download the controller code and to supervise its execution. Preliminary testing of the software is under way and it is expected that initial testing with the building will begin in the Q1 of 1996.

Part III - TECHNICAL INFORMATION

a. Publications Resulting From Award

a1. Refereed Papers


a2. Conference Proceedings Papers and Presentations

2. Goodno, B. J., Craig, J. I., Calise, A. J., and Hsu, C-C., "Hybrid Control of Buildings with Hysteretic Cladding Connection Elements," to appear in the


b. Data on Scientific Collaborators

Dr. Barry J. Goodno, Professor, School of Civil Engineering, Georgia Institute of Technology, Co-Principal Investigator, Project Director

Dr. James I. Craig, Professor, School of Aerospace Engineering, Georgia Institute of Technology, Co-Principal Investigator

Dr. Anthony J. Calise, Professor, School of Aerospace Engineering, Georgia Institute of Technology, Co-Principal Investigator

Dr. Cheng-Chieh Hsu, Graduate Research Assistant, School of Civil and Environmental Engineering (Graduated in August 1995)


Research Description: The objective of the research was to find the optimal cladding design which could be used with a robust H-infinity controller to enhance overall building performance compared to purely passive or active approaches alone. A three step procedure was developed for design of the optimal hybrid control system, and was verified using a case study building structure with an active tendon control system. The active controller was shown to remain stable in the presence of significant changes in the nonlinear behavior of the passive cladding system. The hybrid system resulted in reduced peak displacement response as well as control power reductions for representative earthquake input.

PART IV — FINAL PROJECT REPORT — SUMMARY DATA ON PROJECT PERSONNEL
(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in response to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the information.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

<table>
<thead>
<tr>
<th>A. Total, U.S. Citizens</th>
<th>Senior Staff</th>
<th>Post-Doctorals</th>
<th>Graduate Students</th>
<th>Under-Graduates</th>
<th>Other Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Total, Permanent Residents</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U.S. Citizens or Permanent Residents:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>American Indian or Alaskan Native</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asian</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black, Not of Hispanic Origin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hispanic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pacific Islander</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White, Not of Hispanic Origin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C. Total, Other Non-U.S. Citizens

<table>
<thead>
<tr>
<th>Specify Country</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Germany</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2. Peoples Republic of China</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>3. India</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

D. Total, All participants
(A + B + C)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Disabled</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

☐ Decline to Provide Information. Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

1 Category includes, for example, college and precollege teachers, conference and workshop participants.

2 Use the category that best describes the ethnic/cultural status to all U.S. Citizens and Non-citizens with Permanent Residency. (If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)

3 A person having a physical or mental impairment that substantially limits one or more major life activities who has a record of such impairment; or who is regarded as having such impairment (Disabled individuals also should be counted under the appropriate ethnic/cultural group unless they are classified as "Other Non U.S. Citizens.")

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America and who mainains cultural identification through tribal affiliation or community recognition.

ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia or the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

PACIFIC ISLANDER: A person having origins in any of the original peoples of Hawaii; the U.S. Pacific territories of Guam, American Samoa, and the Northern Mariana; the U.S. Trust Territory of Palau; the islands of Micronesia and Melanesia; or the Philippines.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.
# PART I - PROJECT IDENTIFICATION INFORMATION

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Program Name</td>
<td>EARTHQUAKE HAZARD MITIGATION PROGRAM</td>
</tr>
<tr>
<td>3. Award Dates (MM/YY)</td>
<td>From: 10/94 To: 09/96</td>
</tr>
<tr>
<td>4. Institution and Address</td>
<td>GA Tech Res Corp - GIT Administration Building Atlanta GA 30332</td>
</tr>
<tr>
<td>5. Award Number</td>
<td>9402572</td>
</tr>
<tr>
<td>6. Project Title</td>
<td>Optimal Hybrid Control of Buildings with Nonlinear Hysteretic Cladding Connection Elements</td>
</tr>
</tbody>
</table>

You are encouraged to submit your Final Project Report electronically through the NSF FastLane home page (www.fastlane.nsf.gov).

This Packet Contains NSF Form 98A And 1 Return Envelope
FINAL PROJECT REPORT

Optimal Hybrid Control of Buildings
With Nonlinear Hysteretic Cladding Connection Elements

NSF Award Number CMS-9402572

October 1, 1994 to September 30, 1996

PI/PD NAME AND ADDRESS

Dr. Barry J. Goodno, Co-PI, PD
School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0355
Tel.: (404)894-2227
FAX (404)894-2283

Dr. James I. Craig, Co-PI
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0150
Tel.: (404)894-3042
FAX (404)894-2760

Dr. Anthony J. Calise, Co-PI
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0150
Tel.: (404)894-7145
FAX (404)894-2760

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org.: Dr. Shih-Chi Liu, NSF
2. Program Name: Earthquake Hazards Mitigation Program
3. Award Dates: October 1, 1994 to September 30, 1996 (not including 3 month report completion period)
4. Institution and Address: Georgia Institute of Technology Atlanta, Georgia 30332-0355
5. Award Number: NSF Grant CMS-9402572
6. Project Title: Optimal Hybrid Control of Buildings with Nonlinear Hysteretic Cladding Connection Elements
Part II - SUMMARY OF COMPLETED PROJECT

Summary
Experimental and analytical investigations of hybrid control systems, designed to combine passive damping provided by cladding-structure interaction with robust active control systems, have been carried out in this research program. The passive control forces are introduced through hysteretic interaction between heavy architectural cladding and the supporting structure while the active control forces are assumed to be generated by servo-controlled bracing or mass damping systems. The research was organized into three primary tasks: (1) development of new low-dimensional controller designs for robust control of building structures; (2) development of hybrid design approaches for optimization of the combined active (control) and passive (cladding) systems; and (3) experimental verification through simple scale model lab testing.

The principal products of the research are: (a) new approaches to designing low-dimensional controllers in output feedback settings that can be used for robust control of building structures; (b) integrated design methods for active/passive control systems in which the design process concurrently optimizes active and passive subsystem properties; (c) modeling, analysis and synthesis procedures along with representative designs which combine advanced cladding systems with several different active control systems (e.g., active bracing or variable stiffness systems) to form economical hybrid control strategies; (d) development of improved computer models and extension of present software to include consideration of techniques for hybrid control of buildings using architectural cladding; (e) verification of basic hybrid system behavior through scale model lab experiments. Detailed results are summarized in a series of published papers and conference presentations (listed below).

Part III - TECHNICAL INFORMATION

a. Publications Resulting From Award

a1. Refereed Papers


**Conference Proceedings Papers and Presentations**


b. Data on Scientific Collaborators

Dr. Barry J. Goodno, Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology, Co-Principal Investigator, Project Director

Dr. James I. Craig, Professor, School of Aerospace Engineering, Georgia Institute of Technology, Co-Principal Investigator

Dr. Anthony J. Calise, Professor, School of Aerospace Engineering, Georgia Institute of Technology, Co-Principal Investigator

Dr. Cheng-Chieh Hsu, Graduate Research Assistant, School of Civil and Environmental Engineering (Graduated in August 1995)
Research Description: The objective of the research was to find the optimal cladding design which could be used with a robust H-infinity controller to enhance overall building performance compared to purely passive or active approaches alone. A three step procedure was developed for design of the optimal hybrid control system, and was verified using a case study building structure with an active tendon control system. The active controller was shown to remain stable in the presence of significant changes in the nonlinear behavior of the passive cladding system. The hybrid system resulted in reduced peak displacement response as well as control power reductions for representative earthquake input.

Guohui Gong, Graduate Research Assistant, School of Aerospace Engineering

Ulrich Vollmer, Graduate Research Assistant, School of Civil and Environmental Engineering