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DECENTRALIZED OVERLAPPING CONTROL FOR CIVIL STRUCTURES

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Summary: *This paper presents the problem of overlapping decentralized control design for a 20-story building benchmark which was proposed by the ASCE to the structural control community to compare different control design methods. The control design problem is focused on an in-plane (2-D) analysis and synthesis of one-half of the building structure. This naturally suggests the overlapping decomposition of a finite element overall dynamic model into two subsystems sharing a common parts. The lower substructure is composed of floors 1-12, while the upper substructure is composed of floors 8-20. The overlapping appears in the part of the columns between the 8th and the 12th floors. Fault-tolerance under selected failures of the overall decentralized controller are experimentally tested. The idea of decentralization of control has been numerically tested using a MATLAB/SIMULINK scheme and compared to the benchmark sample centralized control design using the linear quadratic Gaussian (LQG) design. The performance of the overlapping decentralized control design has been assessed by means of given benchmark evaluation criteria, time responses and natural frequency analysis for both pre-earthquake and post-earthquake high-fidelity benchmark models. It is shown that the dynamics of closed-loop benchmark models with the proposed overlapping controller exhibits an acceptable behavior though slightly worse than in the centralized case.*

1. INTRODUCTION

Complex dynamic systems arise in every area of contemporary science and are coupled with a wide variety of real-world phenomena. It looks rather impractical to develop an overarching theory that can cover all their essential features. This does not imply that there is no value in abstracting the common properties of large scale complex systems. This type of knowledge can be very useful. Such an effort has given rise to numerous theoretical and practical results. Large scale systems require control laws whose computation is efficient, and whose operation and implementation entails a minimum amount of information exchange amount the subsystems. Particularly, is is necessary to develop versatile algorithms that can cover a wide range of information structure constraints. It leads to the development of the theory synthesizing control laws under decentralized information structure constraints [1, 2, 3, 4, 5, 6, 7].

Control of flexible structures represents a new, difficult and unique problem, with many complexities in the processes of modeling, control design and implementation [8], [9], [10], [11], [12], [13]. However, most structural control strategies are centralized. It means that system output data collected by all sensors are fed into the centralized controller and sent to all actuators in a centralized manner. It is difficult to transmit huge amount of data between a set of distributed sensors and a central controller as well as to design such a controller. Moreover, if the centralized controller fails, the operation of the overall system can be essentially disrupted. Decentralized control, system decompositions and model simplifications were developed to overcome these difficulties. Local decision units, i.e. controllers, operate with only local information about the overall system through its outputs and influence only a part of the overall system through the system inputs.

Benchmark structural models have been proposed as challenging problems to the structural control community to design and compare control schemes for flexible structures subjected to strong wind or earthquake excitations [11], [14], [15], [16] in recent years. Decentralized control strategies have been tested for benchmark finite element models of cable-stayed bridges for instance in [3] and [17]. Decentralized control strategies for building structures have been applied on finite element models (FEM) in [18] and [19], while [20], [21], [22], [23], [24], [25], [26], [27], [28] have considered lumped models.

This paper is devoted to the decentralized control design using overlapping decomposition applied on the ASCE 20-story steel building benchmark control problem proposed in [11]. Two overlapping subsystems are considered. The lower substructure is composed of floors 1-12, while the upper substructure is composed of floors 8-20. The overlapping appears in the part of the columns between the 8th and the 12th floors. The proposed decomposition serves only as a prototype illustrative case to illustrate the potential of this approach. Trial-and-error minimization of the number and location of sensors and actuators is performed. There are available resulting 6 sensors (accelerometers) and 40 actuators (hydraulic dampers). The proper LQG design is performed on independent appropriately reduced models of subsystems. Four different records of real-world historical earthquakes are used for each simulation run. Two different models are used for each run, i.e. pre-earthquake and post-earthquake structures which differ in the values of the system parameters. The performance is evaluated by using 16 evaluation criteria, dynamic responses and natural frequencies. Moreover, fault-tolerance capability of the proposed decentralized overlapping controller under selected failures in gain matrices is tested. The benchmark problem includes the results of the sample example which is based on the centralized control LQG design. This case is selected as a reference case. The proposed structure with 6 sensors and 40 actuators essentially reduces their numbers compared with the sample example where 5 sensors and 50 actuators are used. The method is summarized as Algorithm. The SIMULINK block diagram for the decentralized overlapping control is supplied.

Note that up to the authors knowledge, decentralized overlapping controller issues for civil structures have been addressed very rarely.

2. PROBLEM FORMULATION

The goal is to derive the methodology of decentralized overlapping LQG design to mitigate responses on the earthquakes. A 20-story benchmark building structure is used to verify this approach. A complete physical description of the building benchmark problem, i.e. in-plane (2D) finite element model and MATLAB/SIMULINK simulation framework, performance evaluation criteria including a sample example, is given in [11]. The input excitation of the building structure is supposed to be one of the four real world historical earthquake records: (E_1) *El Centro* (1940), (E_2) *Hachinohe* (1968), (E_3) *Northridge* (1994), and (E_4) *Kobe* (1995). The N-S component of each earthquake record is used as the model input. Each proposed control strategy is evaluated for all earthquake records. The models, number and location of sensors and actuators should be proposed. A basic overlapping decomposition into two subsystems is considered as a prototype case. The lower substructure is composed of floors 1-12, while the upper substructure is composed of floors 8-20. The overlapping appears in the part of the columns between the 8th and the 12th floors. Sensors and actuators are allowed also in the overlapped part.

2.1 The Problem

The Problem is formulated as follows:

1. Propose operating number of sensors and actuators including their locations on the floors.

2. Design a decentralized overlapping LQG controller for appropriately reduced order subsystems.

3. Perform simulations to assess the dynamic behavior of the benchmark building model when using the implemented decentralized overlapping control as well as the controller failures.

4. Evaluate the performance of the decentralized overlapping scheme including local controllers failures by calculating evaluation criteria, analyzing responses and natural frequencies for all benchmark earthquake excitations.

3. SOLUTION

This section is divided into three parts: Design model and LQG control, Performance and and Results.

3.1 Design model and LQG control

The building structure is decomposed into two overlapping subsystems. The lower subsystem is composed of floors 1-12, while the upper subsystem is composed of floors 8-20. The overlapping appears in the part of the columns between the 8th and the 12th floors. The original mass and stiffness matrices have the order of 540 with two block diagonal blocks of the order

270. These matrices are reduced to 526 DOFs by excluding the elements which are firmly attached to the ground. The matrices describing a lower subsystem S1 are reduced to 256 DOFs. The matrices describing an upper subsystem S2 are not reduced, i.e. their dimensions remain unchanged. Then, the Ritz and Guyan reductions follow. It results in a reduced mass and stiffness matrices of order 135 with a block diagonal structure, where the lower and the upper blocks have the dimensions 63 and 72. The corresponding state-space system has the dimension 270. The subsequent model reduction results in the systems denoted S1R and S2R of the dimensions 32 and 30, respectively." Suppose the sensor models are identical with those used in the sample control design example, but their location and number are different from the sample example. They are located on floors 2,4,8,14,18 and the roof. Hydraulic actuators are selected identically with those ones used in the sample example [11]. It means that the dynamics of the actuators is modeled with a capacity of 897 kN. However, their location and number is also changed. Sensor and actuators appear in the interconnection, i.e. between the 8th and the 12th floors. A total of 40 actuators are used. The numbers of actuators and their location on the floors are based on the analysis of physical properties, the decomposed overlapping structure and simulations. These numbers are from the bottom to the roof 2,1,1,1,1,1,1,1,1,2,3,4,4,4,3,2,1,1,3,3. It remains to add 20 equations of the actuators which are divided as 12 and 13 for the subsystems S1R and S2R, respectively. Therefore, the closed-loop reduced-order control design system SRC has the dimension 87 with the local closed-loop subsystem dimensions of order 44 and 43.

Recall that the resulting controller gain matrix K has the dimensions 20x87. It is composed of the block matrices K1 and K2 of dimensions 12x43 and 13x44, respectively. The resulting observer gain matrix L has the dimensions 87x6. It is composed of the block matrices L1 and L2 of dimensions 44x2 and 43x3, respectively.

A decentralized control law is proposed for each free subsystem by combining its model reduction and the LQG design on the reduced order subsystems. The proposed methodology is summarized as an algorithm:

Algorithm

1. Select initial redundant number of sensors and actuators including their location and models. Implement it into the overall FEM model.

2. Consider pre-define location and models of sensors and actuators according.

3. Expand the original FEM model with identified overlapping subsystems into a larger expanded space and neglect couplings.

4. Perform model reduction for each subsystem. It includes a Ritz transformation followed by a Guyan reduction and apply a balanced realization on final state-space representation of each subsystem. Select a minimal order of the subsystem’s states ensuring the stability of the reduced-order models.

5. Perform the LQG design with preselected weighting matrices for reduced order subsystems.

6. Contract and implement obtained local controllers into the original overall FEM model and run simulations.

7. Evaluate the results by computing given benchmark evaluation criteria, dynamic responses and closed-loop system natural frequencies, all in comparison to the centralized sample control design example as a reference case.

8. Tune the control laws by repeating the simulations for different weighting matrices until acceptable results are reached.

9. If the performance is satisfactory reduce appropriately a set of sensors or actuators and go to step 2 with a new pre-defined structure of sensors and actuators, else go to step 10.

10. End.

The algorithm presents the decentralized design of decentralized LQG controllers using overlapping decomposition. Decomposition at the level of the original FEM model is necessary because the subsequent model reduction operate only with the subsystem's states. The model reduction and the LQG design are performed using well-known algorithms. MATLAB/SIMULINK and Control System Toolbox are employed in this design and performance evaluation. Fig. 1 shows the SIMULINK block diagram for two decentralized overlapping controllers. Local feedback loops use only local states. There are allowed sensors and actuators in the overlapped part.

3.2 Performance

The proposed control strategy is evaluated for all four earthquake records, with the appropriate responses used to calculate the evaluation criteria, the dynamic responses and natural frequencies for both the pre-earthquake and post-earthquake models. The overall merit of the control strategy is offered in terms of maximum response quantities, the number of sensors and actuators and the total power. The performance evaluation is primarily focused on common three items that is displacement, drift and acceleration under given maximal actuator force and the corresponding dynamic responses. The benchmark performance criteria including the constraints of the devices are surveyed in Appendix. The performance results presented in the sample example by [11] are used as a reference case.

3.3 Results

The simulation results for the four prototype cases are presented. The performance of the closed-loop system operating under the failures of local controllers is evaluated in terms of their upper bounds of gain matrices satisfying the dynamic requirements on the closed-loop system performance. The following cases are considered:

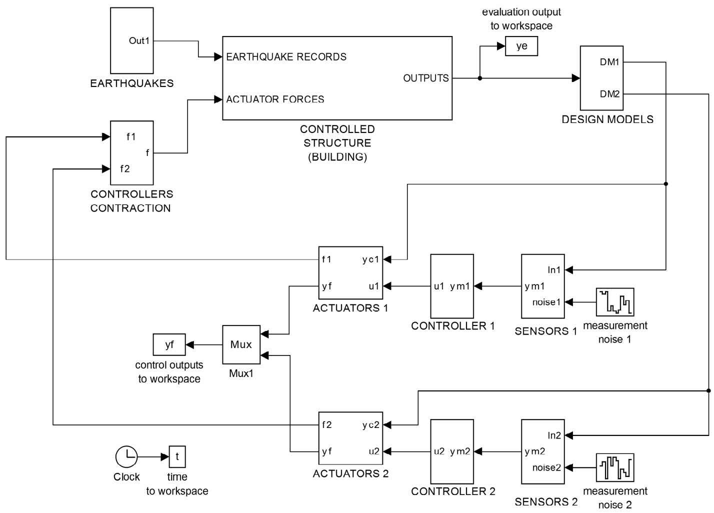


Figure 1: SIMULINK block diagram for the decentralized overlapping control scheme

Case 1. - Decentralized LQG controller design including the model reduction and selection of sensors and actuators. The resulting system has 6 sensors and only 40 actuators.

Case 2. - Total lower local controller failures in the values of gain matrices under fully operating upper local controller are considered.

Case 3. - 30% upper local controller failures in the values of gain matrices under fully operating lower local controller are considered.

Case 4. - 50% overall controller failures in the values of gain matrices are considered.

All simulation results satisfy the requirements on the constraints of the devices for all four earthquake records. The values of the performance criteria are surveyed. Tables present maximal values of the performance criteria over all four earthquakes. 10 natural frequencies are given for Case 1 only because their changes for the remaining cases are negligible. Figures display the responses (Bold) to the Northridge earthquake record and the responses (Solid) of centralized sample example by [11] for the pre-earthquake and the post-earthquake models. The open-loop system responses are included (Dotted). The 20th floor displacement and acceleration as well as the 2nd floor drift responses are displayed on all figures.

	Pre	Post
J_1	0.9001	0.9582
J_2	0.8757	0.9994
J_3	0.9637	0.9982
J_4	0.9348	1.1039
J_5	0.7614	0.7341
J_6	0.7517	0.6712
J_7	0.6979	0.7398
J_8	0.7539	0.6780
J_9	0.0134	0.0114
J_{10}	0.0884	0.1006
J_{11}	0.0171	0.0153
J_{12}	0.0377	0.0341
J_{13}	40	40
J_{14}	6	6
J_{15}	87	87
J_{16}	730.29	617.73

Pre	Post
1.8092	1.4803
3.3656	3.3656
5.1958	4.2511
7.296	7.296
8.9789	7.3464
10.7564	10.338
11.0065	10.7564
12.1808	11.0065
12.6353	12.1808
16.4453	13.5751

Tab. 1: Case 1 - Criteria and natural frequencies for pre- and post-earthquake models

	Pre	Post
J_1	0.9006	0.9581
J_2	0.8755	0.9996
J_3	0.9619	0.9968
J_4	0.9339	1.0954
J_5	0.7617	0.7344
J_6	0.7521	0.6715
J_7	0.6987	0.7396
J_8	0.7542	0.6781
J_9	0.0134	0.0113
J_{10}	0.0887	0.1006
J_{11}	0.0171	0.0153
J_{12}	0.0372	0.0342
J_{13}	40	40
J_{14}	6	6
J_{15}	87	87
J_{16}	728.54	617.16

(a)

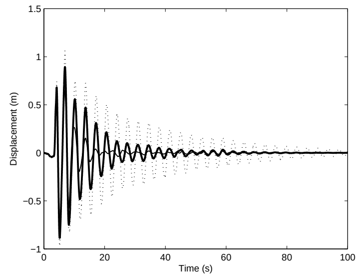
	Pre	Post
J_1	0.9292	0.9705
J_2	0.8929	0.9886
J_3	0.9562	0.9997
J_4	0.9457	1.0771
J_5	0.8051	0.7881
J_6	0.7931	0.7323
J_7	0.7618	0.7771
J_8	0.7956	0.7379
J_9	0.0097	0.0082
J_{10}	0.0971	0.0995
J_{11}	0.0134	0.0121
J_{12}	0.0306	0.0272
J_{13}	40	40
J_{14}	6	6
J_{15}	87	87
J_{16}	526.8	444.61

(b)

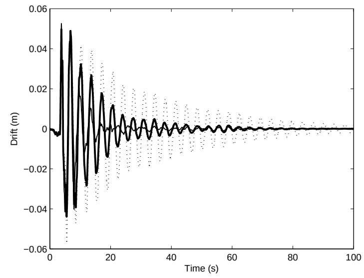
	Pre	Post
J_1	0.9494	0.9787
J_2	0.9185	0.9838
J_3	0.9518	0.9998
J_4	0.9565	1.0546
J_5	0.8426	0.8333
J_6	0.8324	0.7865
J_7	0.8138	0.8261
J_8	0.8366	0.7911
J_9	0.0071	0.006
J_{10}	0.1032	0.0987
J_{11}	0.0103	0.0094
J_{12}	0.0241	0.0217
J_{13}	40	40
J_{14}	6	6
J_{15}	87	87
J_{16}	383.37	324

(c)

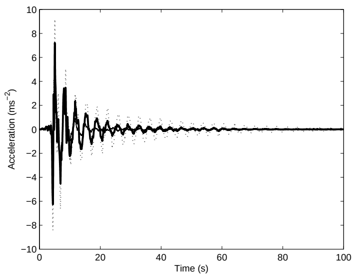
Tab. 2: Criteria under failures of controller channels for pre- and post-earthquake models: (a) 100% lower channel; (b) 30% upper channel; (c) 50% both channels



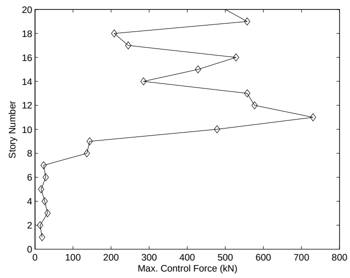
(a) Displacement



(b) Drift

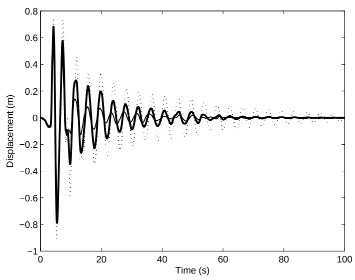


(c) Acceleration

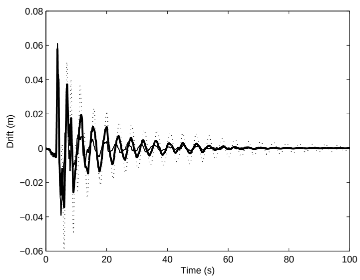


(d) Max. Control Force

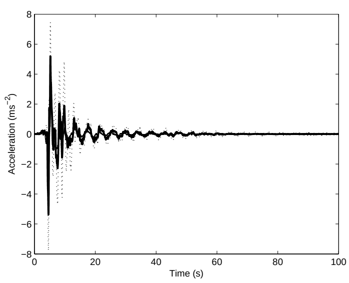
Figure 2: Decentralized overlapping LQG controller - Pre-earthquake model



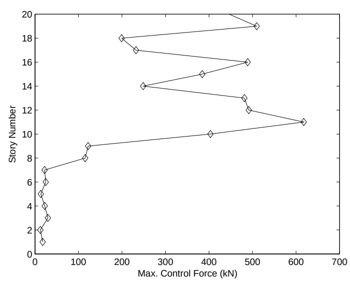
(a) Displacement



(b) Drift

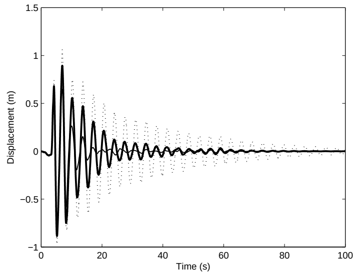


(c) Acceleration

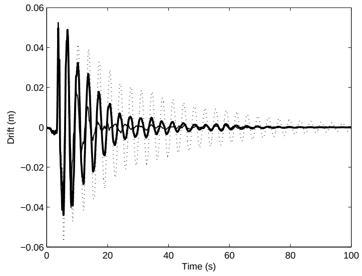


(d) Max. Control Force

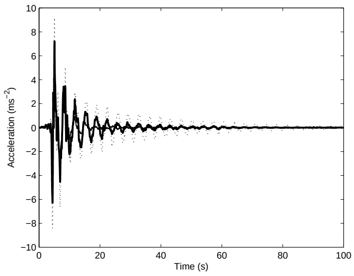
Figure 3: Decentralized overlapping LQG controller - Post-earthquake model



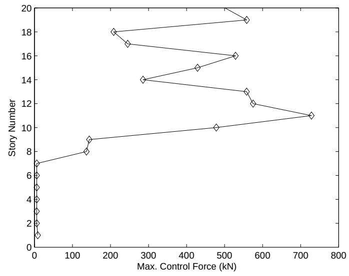
(a) Displacement



(b) Drift

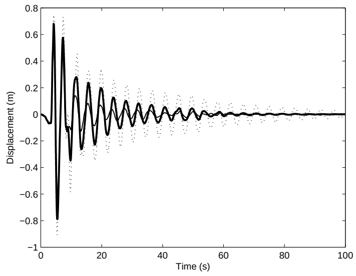


(c) Acceleration

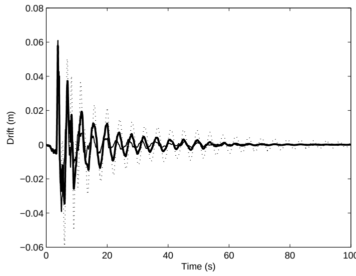


(d) Max. Control Force

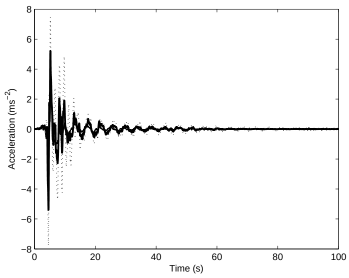
Figure 4: 100% failure in the lower local controller - Pre-earthquake model



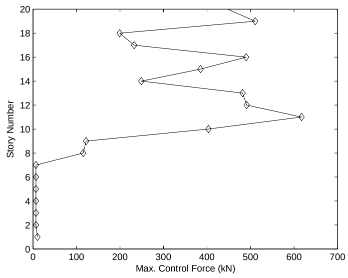
(a) Displacement



(b) Drift

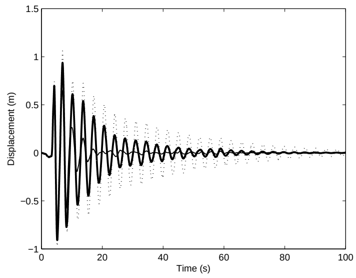


(c) Acceleration

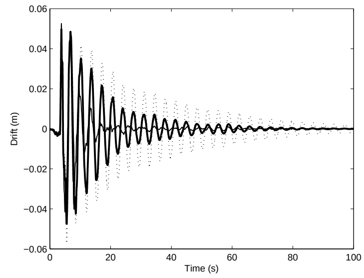


(d) Max. Control Force

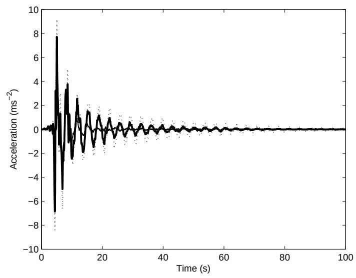
Figure 5: 100% failure in the lower local controller - Post-earthquake model



(a) Displacement



(b) Drift



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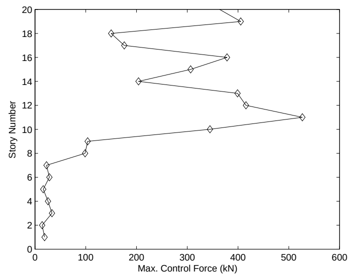
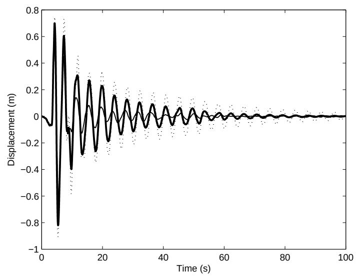
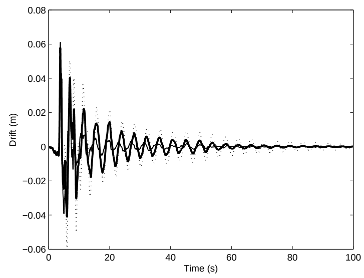


(d) Max. Control Force

Figure 6: 30% failure in the upper local controller - Pre-earthquake model



(a) Displacement



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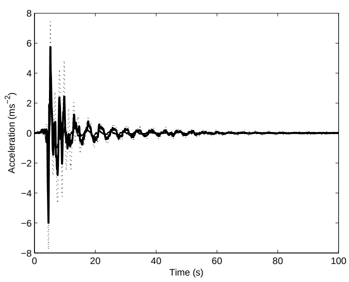

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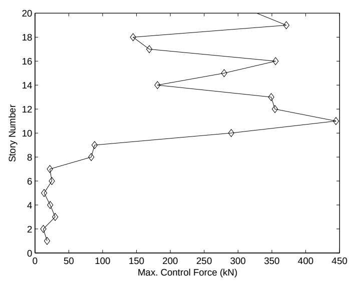
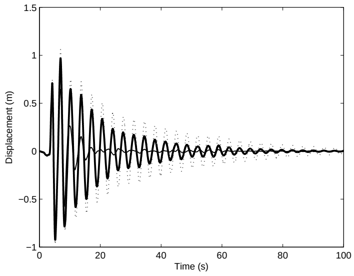
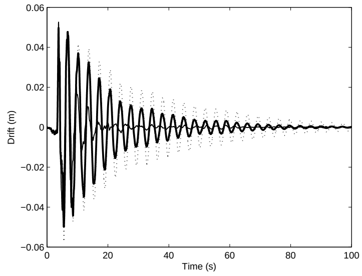


(d) Max. Control Force

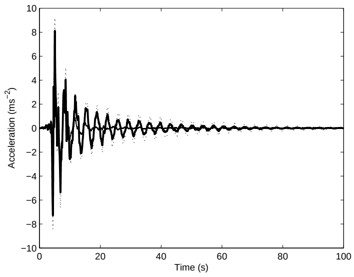
Figure 7: 30% failure in the upper local controller - Post-earthquake model



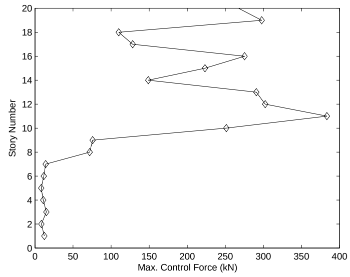
(a) Displacement



(b) Drift

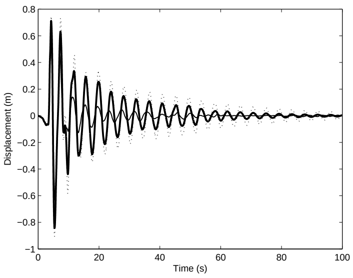


(c) Acceleration

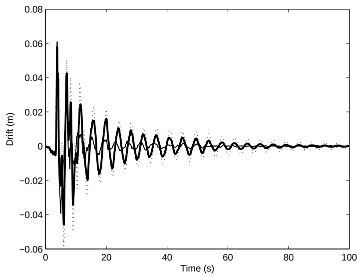


(d) Max. Control Force

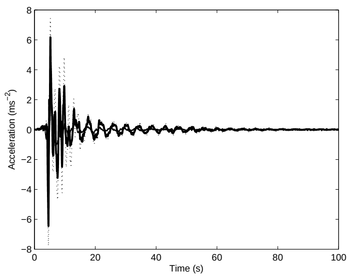
Figure 8: 50% failure in the overall controller - Pre-earthquake model



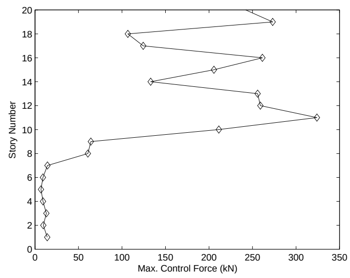
(a) Displacement



(b) Drift



(c) Acceleration



(d) Max. Control Force

Figure 9: 50% failure in the overall controller - Post-earthquake model

4. CONCLUSION

The paper contributes by presenting a new methodology of decentralized overlapping LQG design focused on the 20-story in-plane (2-D) benchmark high-fidelity building FEM model. The performance assessment based on the benchmark evaluation criteria and the analysis of selected responses have been verified for all prototype earthquakes and the pre-earthquake and post-earthquake models including selected failures of local controllers. The results of simulations are promising and confirm expectancy. They are slightly worse than in the case of sample centralized case but lie within acceptable ranges.

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APPENDIX

Appendix surveys the performance criteria including the constraints of the devices. Denote a set of all four earthquakes E. The details of the performance criteria are as follows:

"A systematic evaluation of the performance is based on the evaluation criteria $J_1 - J_{16}$. The criteria $J_1 - J_{15}$ are those used by [11]. The criterion J_{16} has been added. It is the value of a maximal actuator force corresponding with the current simulation run. It is required to keep this value less than the capacity of 897 kN which is allowed for hydraulic actuators. The criteria $J_1 - J_3$ have been selected as the most significant criteria. More precisely, these criteria are defined as follows

$$J_1 = \max_E \left(\frac{\max_{t,i} |x_i(t)|}{x^{max}} \right) \tag{1}$$

where J_1 denotes the maximum displacement over the set of all states $x_i(t)$ corresponding to the horizontal displacement of floors relative to the ground. x^{max} is the maximum uncontrolled displacement corresponding to each respective earthquake.

$$J_2 = \max_E \left(\frac{\max_{t,i} |d_i(t)|}{d^{max}} \right) \tag{2}$$

where J_2 denotes the maximum inter-story drift over the set of all states $x_i(t)$ corresponding to the drift of floors. d^{max} is the maximum inter-story drift corresponding to each respective earthquake.

$$J_3 = \max_E \left(\frac{\max_{t,i} |\ddot{x}_{ai}(t)|}{\ddot{x}_a^{max}} \right) \tag{3}$$

where J_3 denotes the maximum floor acceleration corresponding to the drift of floors. $\ddot{x}_a^{max}$ is the maximum uncontrolled floor acceleration corresponding to each respective earthquake.

A short summary of the evaluation criteria follows:

J_1 - Floor displacement
J_2 - Inter-story drift
J_3 - Floor acceleration
J_4 - Base shear
J_5 - Normed floor displacement
J_6 - Normed inter-story drift
J_7 - Normed floor acceleration
J_8 - Normed base shear
J_9 - Control force
J_{10} - Control device stroke
J_{11} - Control power
J_{12} - Normed control power
J_{13} - Control devices
J_{14} - Sensors
J_{15} - Computational resources
J_{16} - Maximum actuator force

Note that the values of the criteria $J_1 - J_8$ are equal to one, while the values of the remaining criteria are equal to zero for the uncontrolled system. Any successful controller design corresponds with the values of the criteria $J_1 - J_8$ less than one. The post-earthquake model has decreased stiffness caused by assumed structural damages compared with the pre-earthquake model. Simulations have shown that the usage of the post-earthquake model for the control design with a subsequent verification on the closed-loop system composed of the pre-earthquake model with the feedback gain matrices generated for the post-earthquake model is more convenient approach than the usage of the models in an opposite order. Therefore, the proper decentralized LQG design has been performed for the post-earthquake model as the case corresponding with the worst possible scenario", as summarized in [18].

The solved problem employs hydraulic actuators with a capacity of 897kN, a stroke of $\pm$ 8.9cm and the control signal to each control device has a constraint of maximum $\pm$ 10V for each respective earthquake.

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