EARTHQUAKE SAFETY FOR URBAN REGIONS

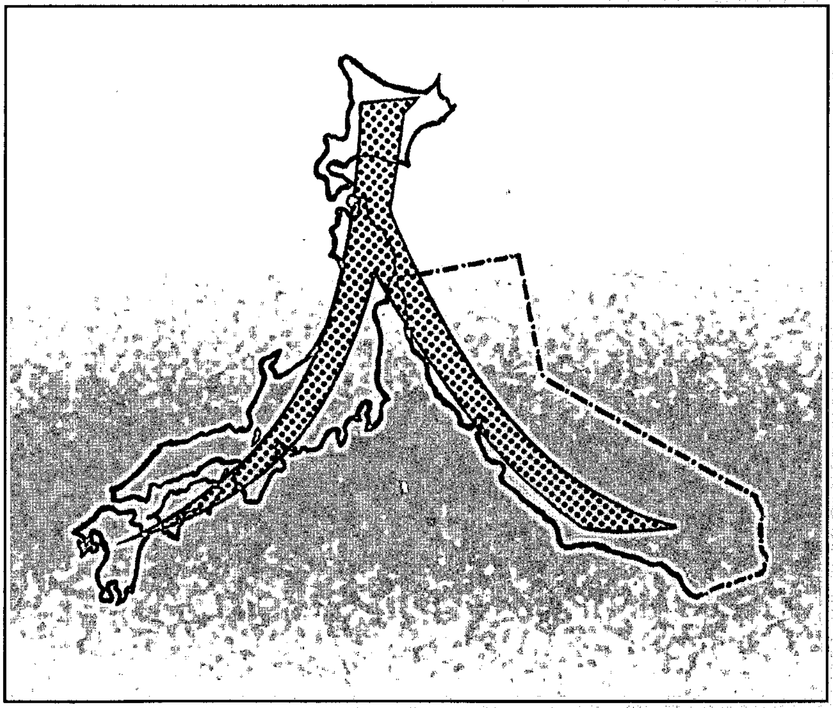
A Joint Research Collaboration

between

Kajima Corporation

and

California Universities for Research in Earthquake Engineering (CUREe)



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FOCUS OF THE JOINT RESEARCH

The theme of Phase II of the CUREe-Kajima Joint Research Program was mitigation of the effects of earthquakes and other natural hazards for safety of urban areas. Joint research was conducted in the following focus areas:

- **Evaluation of the socio-economic consequences of large earthquakes**
- **Reliability-based optimal design**
- **Integrated tools for optimal design**
- **Early warning systems**
- **Near-source ground motion**
- **Modeling of fiber reinforced concrete**

SIGNIFICANT RESEARCH ACCOMPLISHMENTS

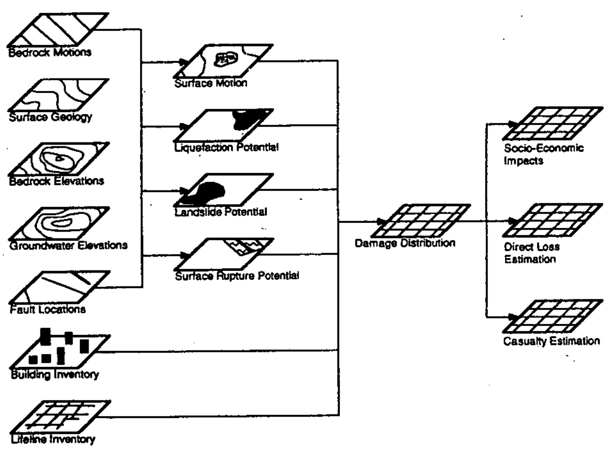
- ***A comprehensive earthquake damage and loss estimation model that incorporates site hazard, ground motion, regional building inventory, lifeline connectivity, and building and lifeline fragility.***
- ***Integration of geographical information systems, relational database management systems, and knowledge-based engineering tools to automate regional earthquake damage and loss estimation including socio-economic impacts.***
- ***An interactive computer program that partially automates the structural analysis, evaluation, and optimization process to allow improved design decisions in the presence of uncertain risk.***
- ***A new approach for determining optimal target reliabilities for the design of reinforced concrete buildings to achieve specific performance objectives over the life of the structure.***
- ***Improved techniques for rapid determination of earthquake location, depth, and source characteristics.***
- ***Improved understanding of the consequences of weld fracture on the seismic performance of steel frame buildings.***
- ***More accurate models for predicting the performance of advanced high-strength concrete and fiber reinforced concrete for use in building and infrastructure systems.***

RESEARCH RESULTS

Methodologies for Evaluating the Socio-economic Consequences of Large Earthquakes

The goal of this research was to develop innovative methods for regional earthquake damage and loss estimation including socio-economic impacts, for the purpose of identifying high risk critical facilities. Evaluation of the socio-economic consequences of large earthquakes required the development of a new comprehensive damage and loss estimation conceptual model.

The conceptual model includes the following key elements: 1) earthquake hazard characterization, 2) geologic and geotechnical databases, 3) building and lifeline component inventories, 4) building and lifeline fragility functions, 5) critical facility evaluation, and 6) socio-economic consequence modeling.



The ground shaking in a region is estimated using either a deterministic or probabilistic approach. The deterministic approach involves specification of all seismic sources affecting the region and assignment of a magnitude to hypothesized events associated with these sources. Source-to-site attenuation relationships and soil amplification factors are also required. The probabilistic approach involves the additional step of determining recurrence relationships for each source so that the probability of exceeding a specified ground motion within a given time interval can be determined.

Past earthquakes have shown that damaging effects of earthquake collateral hazards such as liquefaction and landslides can often surpass the direct effects of ground shaking alone. In this project, data from geotechnical boring logs has been incorporated into a three-dimensional geographic information system model of the region under study. The resulting model is used to determine the site collateral damage potential as well as the site amplification effects.

The development of a complete and detailed inventory of structures is typically the most crucial, time consuming, and expensive component of a regional earthquake loss study. The accuracy of the final estimates of damage and loss is highly dependent upon the accuracy of the underlying structural inventory. The information needed in the inventory includes: location information, use information, and structural property information. Available databases for compiling an inventory are often incomplete, out-dated, inaccurate, or available only in paper format. A variety of data sources was used in this project.

Two classification systems are typically required in the development of an inventory. The first classifies facilities according to their structural response to earthquakes and is used for estimating damage. The second classifies facilities according to their use or social function and is used for estimating monetary and other losses. The use of existing databases required the application of expert opinion or fuzzy logic for assigning the two classifications and for inferring missing data attributes.

A crucial element of the damage and loss estimation methodology is the determination of a ground motion-damage relationship for each structure or class of structures. There are typically four different approaches to this determination: 1) consensus expert opinion, 2) simulation of time histories of ground motion with non-linear dynamic structural analysis, 3) static pushover analysis, and 4) empirical data. The first and third approaches were primarily used in this study.

A major focus of the research was to develop a methodology to identify critical facilities that have the most impact on the socio-economic consequences of an earthquake. The purpose of identifying critical facilities is to provide guidance as to what pre-earthquake mitigation or post-earthquake emergency response actions should be taken to limit the most significant adverse consequences of the earthquake. Adverse consequences are divided into three categories: 1) high dollar losses from direct damage, 2) high casualty losses, and 3) high economic impact due to loss of function. The methodology requires a high resolution inventory in order to assess whether an individual facility is critical.

A final element of the research dealt with determination of the economic feasibility of seismic rehabilitation. Seismic rehabilitation of an existing structure may occur based on a legal mandate or based on economic justification. The study sets forth an approach for determination of the economic feasibility of rehabilitation and applies this approach to the special case of a hospital facility.

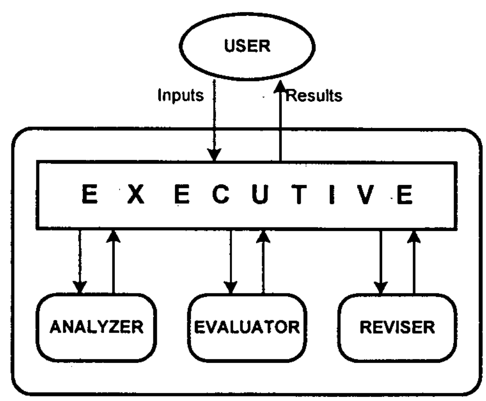
The methodology developed through this research investigation was successfully applied the study of two sites in Tokyo and to the City of Palo Alto in California.

Optimal Design Decisions Under Risk

Making decisions related to a proposed design of a structural system requires searching through a large design space to evaluate possible choices on the basis of multiple criteria. The best, or optimal design is often difficult to define. A structure cannot be designed so that each design objective is optimal. For example, a building cannot simultaneously be the most economical and have large aesthetically-pleasing open spaces, or be very tall and very rigid. Thus, by optimal it is usually understood that the different design criteria are traded-off in some manner to provide a balanced design in which more emphasis is given to the most important design criteria than to other less important criteria.

The goal of this research was to develop an interactive computer program that partially automates the structural analysis, evaluation, and optimization process so that the structural designer may make better design decisions in the presence of uncertain risk. By coupling the design decision-making process with advanced computational tools and artificial intelligence methodologies, the search for an optimal design is significantly improved.

A software package entitled Smart Optimal Design and Analysis (SODA) was developed that allows the user to rapidly evaluate and improve a proposed design by taking into account the major factors of interest related to the design. These factors include not only structural engineering criteria, but also other considerations such as economic criteria. SODA uses new methodologies, such as object-oriented programming, multi-criteria decision theory, fuzzy reliability and stochastic optimization. SODA is designed in a modular fashion so that it can be easily modified to incorporate additional features and to further increase its efficiency and effectiveness.



The design decision-making process begins with a preliminary design and then involves an iterative procedure of analysis, evaluation, and revision. The analyzer module uses finite element analysis to compute performance parameter values based on a building configuration specified by the user and the current values of design parameters. The evaluator is a module based on multi-criteria decision theory and fuzzy reliability that determines an overall design evaluation measure, or level of acceptability, of the current design based on multiple performance criteria and a treatment of load uncertainties. The reviser, performs revisions of the design to find an optimal design, based on maximization of the overall design evaluation measure. Either a deterministic or stochastic optimization algorithm can be chosen.

An executive module performs a supervisory role with respect to the other modules The executive module acts as an interface between the three other modules and the user, assisting in the initialization of the modules, controlling the execution of the different processes, and storing the information associated with the analysis, evaluation and optimization so that it is accessible to each of the other modules.

The user selects the design and performance parameters important for the design decision-making process. These design and performance parameters are combined with preference functions and weights to express the design criteria in a quantitative form Design parameters control the geometry of the structural members while performance parameters represent quantities related to the engineering and economic performance of the design.

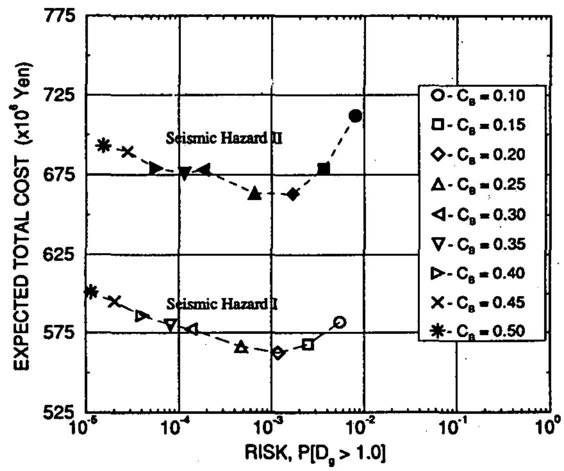
User-supplied preference functions define the preference for each design or performance parameter. The preference functions may be expressed as minimum and/or maximum (fuzzy) bounds on design criteria, or they may expressed as a more complex relationship. In addition, the user supplies importance factors or weights that indicate the relative importance of each design criterion.

Using the tools developed in this research, the designer can more rapidly evaluate and improve proposed designs to explore a broader range of alternatives than would otherwise be economically feasible. An optimal design can be sought based on the evaluation of many major factors affecting the design, including structural performance criteria, client preferences, and economic constraints, as well as the uncertainties associated with the environmental loads the structure may experience during its lifetime.

Reliability-Based Optimal Aseismic Design for R/C Buildings

A primary objective of earthquake resistant design is to insure that the performance of a structure is such that it does not experience excessive damage or collapse under moderate or severe earthquake loads. It is generally accepted that to require complete safety or perfect performance under all possible earthquake loads would be prohibitively expensive. Underling the philosophy of current earthquake-resistant design is the premise that some residual risk or probability of non-achievement of the-performance objectives must be accepted. Determination of an appropriate level of accepted risk requires an examination of the trade-offs between structural performance and economic consequences.

In light of unavoidable and significant uncertainty and randomness in earthquake loadings, and in structural response, appropriate measures of structural safety and performance should be stated in probabilistic terms. Accordingly, criteria for seismic resistant design may be formulated in terms of a probabilistic optimal target system reliability.



This study has developed the necessary reliability framework for the systematic determination of optimal target reliabilities for the earthquake-resistant design of reinforced concrete buildings. Optimal target reliabilities for design to control damage and prevent collapse have been determined quantitatively on the basis of minimum life-cycle cost. The study has also developed new and improved methods for reliability assessment and for reliability-based optimal design.

Optimal target reliabilities are determined on the basis of a trade-off between safety and life-cycle cost so as to achieve minimum expected life-cycle cost. The approach involves the following steps:

1. Using an existing design code, the structure is designed for different levels of earthquake excitation as represented, for example, by dif-

ferent levels of seismic base shear coefficient.
2. The structural damage and reliability is assessed for each design level.
3. For each design level, the total cost of structural damage, including building repair costs and other direct and indirect costs is determined based on data from past earthquakes.
4. The cost is represented as a function of structural reliability, and an expected life-cycle cost function is developed.
5. The optimal target reliability is determined corresponding to the minimum expected life-cycle cost.
6. Finally, the design base shear coefficient corresponding to the optimal target reliability is determined.

A new computational approach for nonlinear random vibration analysis was developed as a part of this study. The approach requires a relatively small number of deterministic time history calculations to compute the statistics of the response and the probabilities associated with various excursion measures. Almost any type of nonlinear model can be analyzed including hysteretic behavior.

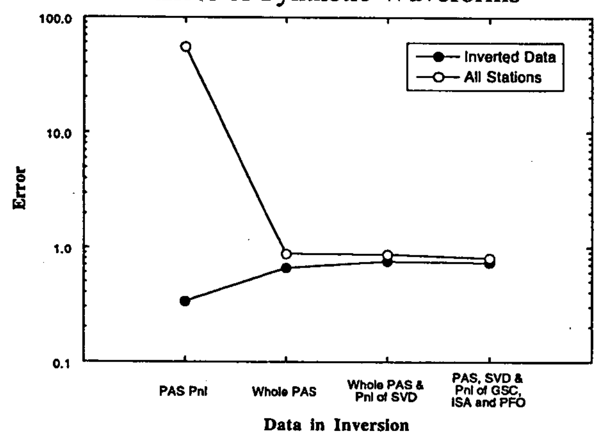
A new algorithm was also developed for minimizing the initial cost of a structure subject to a minimum reliability constraint. This algorithm is globally convergent and does not require second derivatives or repeated reliability analyses, as is required for existing algorithms

In order to demonstrate its usefulness, the new reliability-based methodology was applied to a five-story, ductile moment-resisting reinforced concrete frame building with shear walls. For this study, Kajima engineers provided a set of model building designs for different levels of safety using varying levels of seismic base shear. The optimal base shear coefficient for the subject building was found to be close to the value specified by the Japanese code.

Early Warning Systems

The goal of this research was to further develop the concept of early warning. Specifically, investigations were undertaken to examine the feasibility of finding earthquake location, depth, source mechanism and source-time function using broadband data from a single station or a few stations. Also considered was the problem of using this information to predict strong motions in a region with large variations in crustal structure. A further objective of the research was to construct a preliminary model for data recorded from a small event in Tokyo Japan. Particularly emphasis was placed on depth determination which is an area in which current Japanese early warning algorithms have had difficulties.

Error of Synthetic Waveforms



Studies of the Sierra Madre earthquake of June 28, 1991 demonstrated that inversion results based on Green's functions calculated with an average model of the Southern California crust work well when there is data from more than one station, but inversion for data from just one local station needs more refined Green's functions. This refinement can be performed with small events or a previous moderate event in the same area. An additional refinement would be to incorporate the effects of local receiver structure in ground motion predictions, as the effects on waveforms of lateral hetereogeneities in the crust can be significant. Creating a catalog of empirical Green's functions is most feasible in areas where there is a dense network of broadband stations.

The results of this research suggest that it is possible to predict the ground motions in an urbanized basin from an earthquake on a large nearby fault more rapidly than the seismic energy can propagate through the basin. However, this research represents only a first step in testing of the credibility of the strategy. An early warning system can fail for many reasons. However, the investigators believe that these problems will be overcome as broadband measuring systems are improved and more earthquake data is modeled.

Near-Field Ground Motion Studies

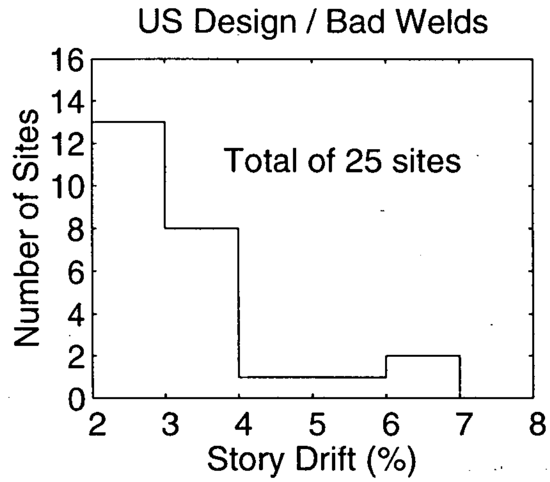
The performance of steel moment-frame buildings designed according to US and Japanese building codes was analyzed by computer simulations for earthquake ground motions containing strong near-field or near-source effects. The ground motions were generated from computer simulations of the 1994 Northridge and 1995 Hyogo-ken Nanbu earthquakes as well as recorded motions from these and other significant events. A major objective of the analyses was to investigate the consequences of weld fracture on the seismic performance of steel frame buildings.

Simulations of the Northridge event provided ground motions on a 12 × 12 grid at a 5-km grid spacing, covering an area of 3600 km^2. Maximum ground velocities and displacements were 175 cm/sec and 61 cm, respectively. The peak ground velocity exceeded 80 cm/sec at 13 sites, and peak ground displacement exceeded 30 cm at 10 sites.

The Kobe event simulation considered sediment and the subsurface rock profile effects and provided a set of motions at a total of 2000 grid points covering an area of 100 km^2. Peak ground velocities exceeded 50 cm/sec over much of the grid area with maximum values exceeding 100 cm/sec.

The structural response analyses included the following features: planar analysis of multiple frames connected together; fiber model for beams and columns; realistic stress-strain relation for steel; weld fracture at beam-to-column connections, column splices and base plates; column uplift; nonlinear panel zones; composite slab action with cracking and yielding; accurate P–Δ and moment amplification effects through geometric updating; basement wall elements; nonlinear foundation springs; nonlinear story shear springs to represent nonstructural contributions to strength and stiffness; nonlinear damping to cap the damping forces; horizontal and vertical ground motion; and sophisticated iteration and time-integration strategies. Weld fracture involves cracking a fiber once a specified tensile strain is reached. Values of these strains are randomly distributed to potential fracture locations.

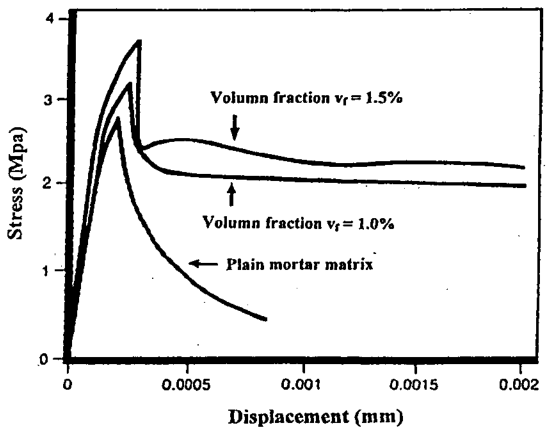
Six building designs were evaluated: a 6-story building based on Uniform Building Code Zone 4 requirements, a 6-story version of this structure based on the Japanese code, a 6-story building with a different layout designed by Kajima engineers, and three corresponding 20-story buildings.



The investigation has shown that near-field ground motions from even moderate earthquakes can produce significant damage in modern buildings over large regions. Building strengthening appears to be of marginal benefit in mitigating such damage, and an effective design strategy is not apparent. Further, larger earthquakes and a weaker building stock whose design is controlled by strength and not drift would make the picture worse. Deterioration mechanisms such as weld fracture will play an even greater role in such cases. The study shows that optimal design levels need to be identified that properly consider the earthquake hazard and economic loss estimates

Modeling of Multiphase Fiber Reinforced Concrete

The goal of this research was to develop advanced micromechanics-based constitutive and damage models for high-strength fiber reinforced multiphase concrete. A micromechanical framework was developed to investigate effective mechanical properties of elastic multi-phase composites containing many randomly dispersed ellipsoidal inhomogeneities. The research examined the effective elastic properties of three-dimensional three-phase random short fiber reinforced concrete.



Studies included investigation of the behavior of two-dimensional three-phase unidirectionally aligned fiber reinforced concrete with randomly distributed microcracks, the stress fields arising from the single fiber pullout system, as well as the local interactions and effective elastic properties of two-dimensional two-phase unidirectionally aligned, randomly dispersed fiber reinforced concrete.

The elastic stress fields arising from the single fiber pull-out system with different geometric and material parameters were obtained by using linear elastic finite element analysis. A two-dimensional Green's function was employed to micromechanically solve the problem of local interactions between two arbitrarily located circular fibers, and approximate analytical solutions were obtained.

Innovative Constitutive Modeling of Fiber Reinforced Concrete

Effective transverse elastic moduli of two-phase brittle matrix composites containing many randomly located yet unidirectionally aligned circular fibers were investigated in this study. The fibers were characterized as infinitely long and equal-sized inclusions. By employing the local and probabilistic pairwise fiber interaction formulation, coupled with the ensemble-volume averaged field equations, a novel and accurate method for the predicting the effective transverse elastic moduli of two-phase fiber reinforced composites was developed.

The proposed approach was extended to predict the effective transverse shear viscosities of fiber suspensions with randomly located aligned rigid fibers. Comparisons with experimental data and variational bounds were also made to illustrate the potential predictive capability of the new method for analysis of fiber-reinforced composites.

An analytical formulation for the elastic stress fields of the single fiber pullout problem was also developed. The new formulation is more general and realistic than previous formulations. Preliminary numerical results have been obtained to illustrate the behavior of the new formulation for the fiber-matrix interface.

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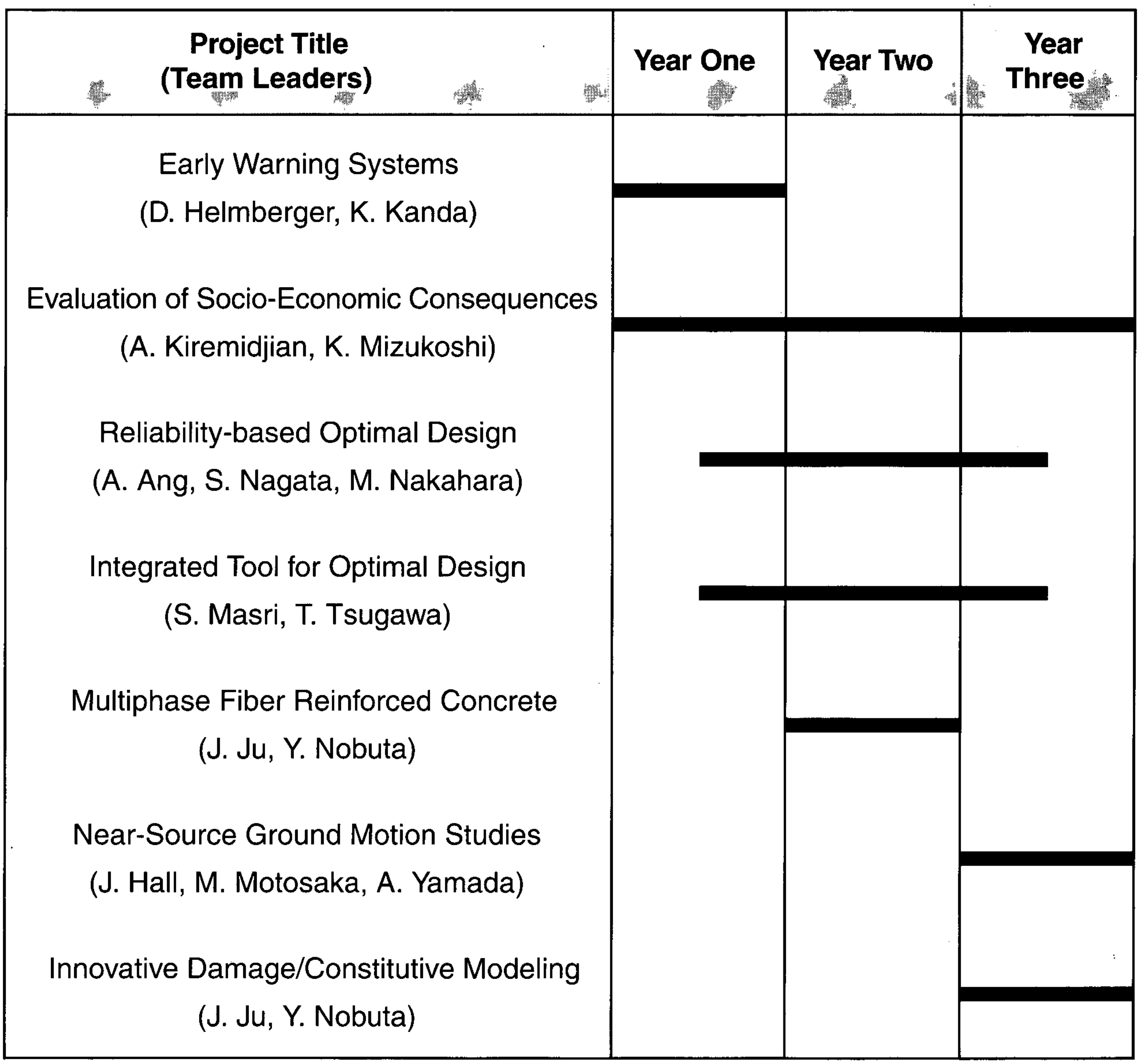
Research Plan

MITIGATION OF THE EFFECTS OF EARTHQUAKES AND OTHER NATURAL HAZARDS FOR SAFETY OF URBAN AREAS



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