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# EVALUATION FRAMEWORK OF DISASTER MITIGATION MEASURES FOR MAKING EARTHQUAKE-RESILIENT COMMUNITIES

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## *Abstract*

For mitigation of earthquake disasters, various technologies to apply for urban communities are being developed. These technologies, however, are sometimes difficult to use in actual applications due to little incentives for owners of buildings or infrastructures because the owners cannot calculate their cost-effectiveness and therefore consider the payment for installation of the technologies as a cost to be reduced. To solve this problem, we, *National Research Institute for Earth Science and Disaster Resilience*, are making a research to construct a framework that makes adaptation of such earthquake-disaster-mitigation measures easier and thus urban communities more earthquake-resilient, together with *The University of Tokyo*, *The Japan Society of Seismic Isolation*, and *Hitachi, Ltd*. This framework consists of two elements; one is a certification process of earthquake-disaster-mitigation measures and the other is "urban cyber-physical system (CPS)" that could evaluate earthquake-resistant capability of buildings and/or social infrastructure. In the certification process, a newly-developed earthquake-mitigation measure would be reviewed and then certified when its effect satisfies a predetermined standard. This certification is expected to give proper information of the measure in quality to owners of buildings and/or infrastructures for making their decisions. The urban CPS would have "Information platform" that is a numerical model database of buildings and/or infrastructure in a considered urban community and "Simulation platform" that is a computational simulation resource. The CPS output of quantitative effect evaluation of the measures is expected for the owners to understand the cost-effectiveness of the installation of the measures. To construct the CPS, the followings are needed: (1) Construction and continuous update of Information platform through data aggregation and analysis of existing vibration data of structures, data set of building information modeling (BIM) or construction information modeling (CIM) and other various available databases, and (2) Development of Simulation platform that has two functions; a prediction function to calculate behaviors of urban communities and infrastructures during earthquakes by using the data in Information platform and an identification function to identify the structural system from the relation between input earthquake motions and responses of the structure. In addition, this framework requires establishment of eco-system to operate, continue and develop it. This paper discusses on this matter as well.

*Keywords: Earthquake-resilience; Certification; Cyber-Physical System; Eco-system*

## 1. Introduction

Mitigation of earthquake disasters is always a high-priority challenge in earthquake engineering. From the lessons from recent earthquake disasters, not only reducing number of casualties but also continuing functions of urban communities are important for economic and social recovery from earthquake damages. Therefore, resilience of urban communities, in this sense, must be enhanced by introducing appropriate measures. For this purpose, various technologies are being developed and proposed. These technologies are, however, sometimes difficult to use in actual applications due to little incentives for owners of buildings or infrastructures because the owners cannot calculate their cost-effectiveness and therefore consider the payment for installation of the technologies as a cost to be reduced. Therefore, a framework that encourages the owners to invest in seismic capability enhancement is expected to be developed and widely used. It should be noted that this is consistent with the *Grand Challenges* that the National Research Council of the USA prepared for National Science Foundation in 2011, that is, "Community Resilience Framework," "Decision Making," "Simulation," "Mitigation" and "Design Tools" [1]. Also, Science Council of Japan has published a proposal "*Dai-shinsai no okinai toshi wo mezashite* (Toward an urban community without earthquake disasters)" in 2017 that defines challenges in modern metropolitans on readiness for future large earthquakes and encouraged scientists and engineers to contribute earthquake disaster prevention [2]. These grand challenges and proposal are yet new.

To achieve this goal, we, *National Research Institute for Earth Science and Disaster Resilience* (NIED), are making a research to construct a framework that makes adaptation of earthquake-disaster-mitigation measures easier and thus urban communities more earthquake-resilient, together with *The University of Tokyo, The Japan Society of Seismic Isolation* (JSSI), and *Hitachi, Ltd*. This framework consists of two elements; one is a certification process of earthquake-disaster-mitigation measures and the other is "urban cyber-physical system (CPS)" that could evaluate earthquake-resistant capability of buildings and/or social infrastructure. This paper describes the concept of the framework and its eco-system to operate.

## 2. Proposal of evaluation framework

The framework proposed here is schematically shown in Fig.1. Activation of the process of delivering earthquake-disaster-mitigation measures from suppliers to users makes communities more resilient to earthquake hazards. Here, two elements are proposed to be introduced. One is a "certification process" and the other is "urban cyber-physical system (CPS)." In the certification process, a newly-developed disaster-mitigation measure would be reviewed and then certified when its effect satisfies a predetermined standard. This certification is expected to give proper information of the measure in quality to owners of buildings and/or infrastructures for making their decisions. The urban CPS would have a numerical model database of buildings and/or infrastructure in a considered urban community and a computational simulation resource that can output quantitative effect evaluation of the measures. This output is expected for the owners to understand the cost-benefit performance of installation of the measures. These two elements would give the owners proper information on disaster-mitigation measures for making their investment decisions. Note that this framework would support the introduction of earthquake-disaster-mitigation measures for earthquake-resilient communities and therefore developments of such measures are yet important. We, NIED, are making R&D for development of a new-type of isolation system. This is presented elsewhere in this conference [3, 4].

## 3. Certification process

The certification process for a newly-developed earthquake-disaster-mitigation measure would be similar to certification systems of other industrial products/services, as shown in Fig.2. The processes are operated by third-party organizations with credibility. The standards and the reviewing process are predetermined and open to public. Then, suppliers, such as solution providers, manufacturers and developers can understand the level of required functions, reliabilities and so on for the certificates and thus properly prepare the review for certificates. Also, they can estimate the volume of efforts to develop such measures. After completing development and obtaining the certificate, the suppliers can use the certificate to explain capabilities and effects of their products/services to users. These effects are expected to accelerate R&D activities to create new products/services. Under the confidence on the certification systems, the users accept the quality level of the products/services so that they would make decisions focusing on other conditions such as prices, delivery time and so on. Therefore, both of the suppliers and the users can take advantages from the certification process. As for the earthquake-disaster-mitigation measure certification, the effect of the measure must be verified with simulations or experiments. Through these verification activities, it would be possible to construct numerical models of the measures to describe their performance. It is desirable to establish a scheme that the numerical models of the newly-developed measures are provided to the urban CPS (discussed in the following chapter in details), for simulations of seismic performance of urban areas. It should be noted that each country has its own building act, e.g. Building Standard Ant in Japan, to keep building structure safety. Therefore, the certificate system must follow the acts when needed.

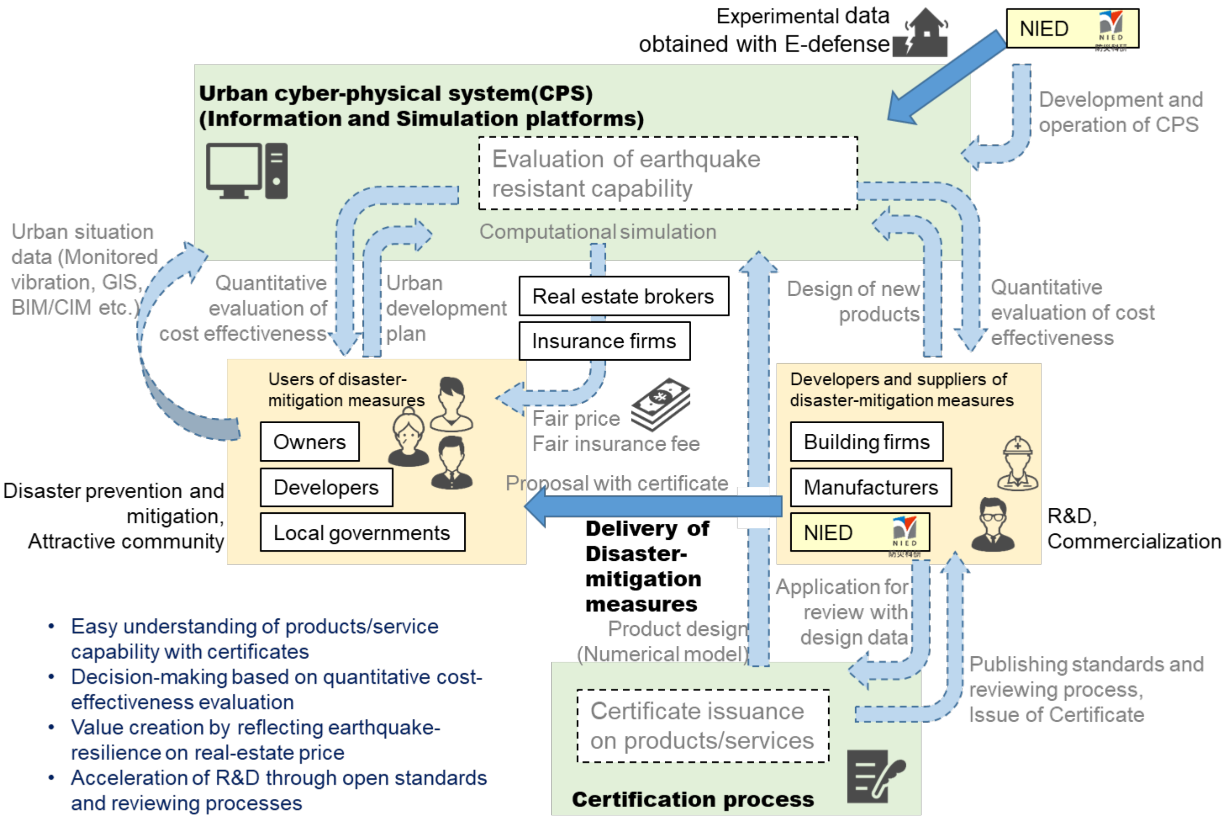


Fig. 1 – Concept of the proposed framework

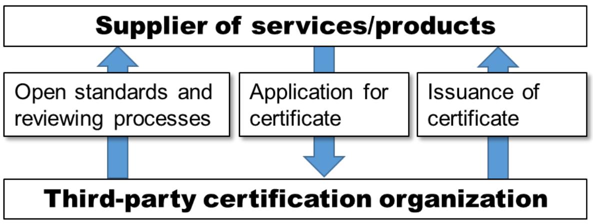


Fig. 2 – Certification process



 

## 4. Urban cyber-physical system

"Urban cyber-physical system (CPS)" is the system that could evaluate earthquake-resistant capability of buildings and/or social infrastructure. The urban CPS proposed here consists of two platforms; "Information platform" that is a numerical model database of buildings and/or infrastructure in a considered urban community and "Simulation platform" that is a computational simulation resource, as shown in Fig.3. The CPS output of quantitative effect evaluation of the earthquake-disaster-mitigation measures is expected for the owners to understand the cost-effectiveness of the installation of the measures. The features of the two platforms and the supposed use cases of this urban CPS will be described in the followings.

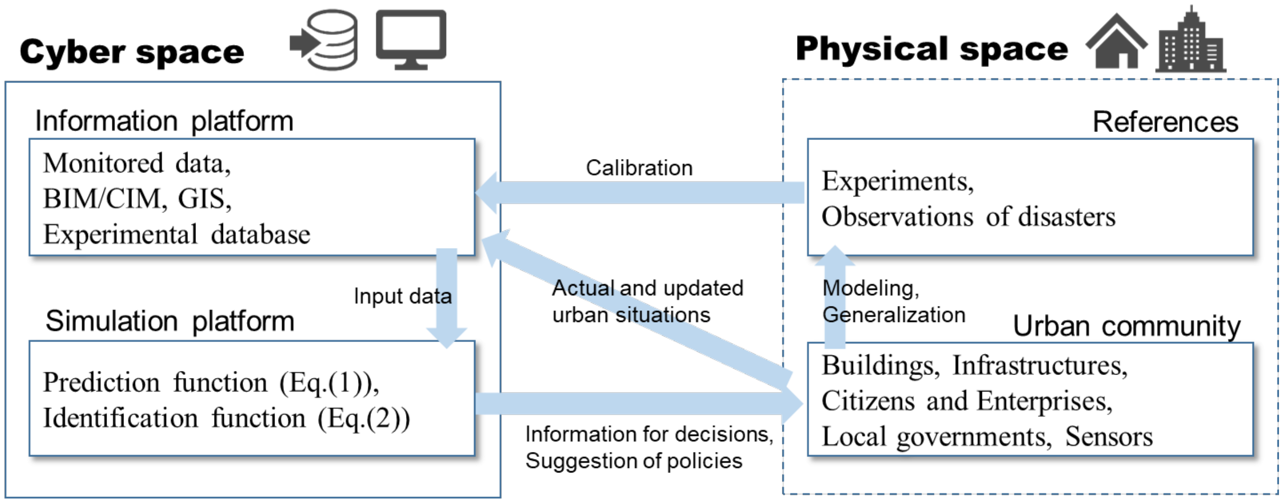


Fig. 3 – Concept of the urban cyber-physical system

### 4.1 Information platform

Information platform is a database of numerical models for evaluation of resilience and readiness against earthquake hazards in communities (Physical space) and necessary to construct based on actual situations and to update continuously. This would become possible through data aggregation and analysis of existing vibration data of structures, data set of building information modeling (BIM) or construction information modeling (CIM) and other various available databases. In particular, utilization of existing vibration data obtained from sensors attached to structures is essential to reflect variations of community situations. Various stakeholders in communities, such as building owners, developers, building firms and local governments have already prepared and operated their own monitoring systems for their own purposes. The monitored data, however, are not usually shared with others because such data may include confidential information. To promote data sharing for constructing broader community database, we plan to apply the concept of "IoT-HUB" [5] as shown in Fig.4. As written above, each stakeholder constructs its own private cloud including acceleration sensors to monitor building vibrations. A private cloud is shown with a cylindrical column and figuratively called here as a "Silo." The vibration data in the different Silos are not necessarily transferred on the same protocol. The "IoT-HUB" is a Web-API system to connect different Silos. The IoT-HUB is composed of two blocks. One is the Application Program Interface (API) block. This block is an application coded with generally-used computer languages such as Hypertext Transfer Protocol (HTTP) and JavaScript Object Notation (JSON) and sends *Things* (data and/or other related information) in each Silo. The other is machine Interface (I/F) block. This block stores "Cloud Drivers" managing the protocol of each silo by its administrator. The Cloud Driver can define some restrictions, e.g. to filter some specific commands to keep their intellectual properties. These features are expected to make it easy for the stakeholders to compromise public benefit and private profit.

Another of interest for constructing Information platform is to make simulation-available models from BIM/CIM information. Recently, BIM and CIM are becoming prepared and used in construction and maintenance of structures. Since BIM/CIM data have various kinds of actual and updated structural information, it is useful to employ for understanding community situations. As described in the next section, Simulation platform is a computational simulation resource that requires finite-element numerical models including meshing information, material constants and boundary conditions. BIM/CIM data, however, do not hold such necessary information in a ready-to-use format because BIM/CIM data structures are defined for different purposes. For making finite-element numerical models from configuration and material information, the authors have developed an application program [6]. Therefore, development of a function to extract necessary configuration and material information from BIM/CIM data and connecting this function to the above-mentioned model generation application would make it possible to construct the detailed finite-element structural model.

In the above, numerical models of individual structures were discussed. The model of urban communities can be constructed by connecting such individual models on geographic information system (GIS). Connecting GIS and such numerical models gives us location information of the building structure. Also, it is possible to construct comprehensive and simple three-dimensional structural model from market-available GIS data such as polygon representation data of buildings and information of their number of stories. Here, it is possible to use an already-established method for automatically making a multiple-degree-of-freedom (MDOF) model that may be used for physical simulation of buildings [7]. Therefore, it is necessary to decide data formats and specifications by considering the purpose and scale of simulation.

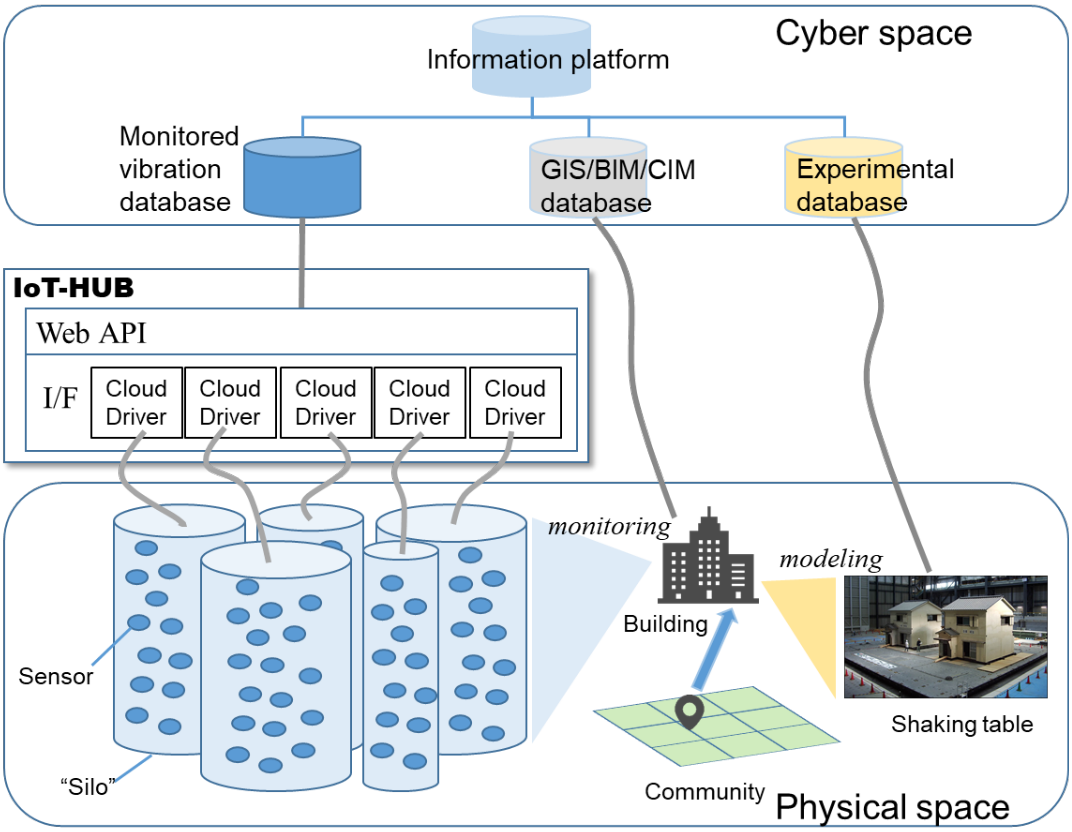


Fig. 4 – Conceptual view of IoT-HUB

## 4.2 Simulation platform

Simulation platform is a computational simulation resource for evaluation of response and performance of communities against earthquake hazards and expected to have the following two functions; a prediction function to calculate behaviors of urban communities and infrastructures during earthquakes by using the data in Information platform and an identification function to identify structural system parameters from the relation between input earthquake motions and responses of the structure.



 

The prediction function is to evaluate response of structures and other elements in a community with an urban community model to an input ground motion like an earthquake; namely,

$$Response = f\,(Urban\ community\ Model,\ Input\ Ground\ Motion). \tag{1}$$

The output of the prediction function can be used on decision-makings on investments to earthquake-disaster-mitigation measures. Also, at the moment of earthquake hazards, this may be used for understanding situation of damages and reacting promptly. Here, this simulation is conducted by using urban community model consisting of comprehensive MDOF model and/or detailed Finite Element Method (FEM) model for specific areas of interest. In the simulation, it is needed to introduce a flexible simulation framework that can treat various types of meshing model such as MDOF model, 2-dimesional frame model, 3-dimensional frame model or 3-dimensional solid model by considering calculation resources and available information for constructing the urban community models. It is also required to take care of multi-physics and multi-scale simulations like soils, structures, interior facilities and social activities. Moreover, it is an important problem to develop data-driven simulation by referring monitored data in the urban community area. Therefore, it is necessary to prepare a development framework of simulation using programming technologies such as object-oriented programming with flexibility and scalability and template meta-programming for responding various types of needs. When the object-oriented programming is applied to a large-scale simulation, the calculation performance might be lower. However, a design pattern for obtaining higher performance [8] and a large-scale parallel FEM solver using object-oriented programming technique [9] have been developed. Under these circumstances, it might be effective to re-design the physical simulation program for the urban CPS.

The identification function is to evaluate situations of structures and other elements in a community with the response to an input ground motion like a micro tremor or a small-size earthquake; namely,

$$Urban\ community\ Model = f^{-1}\,(Response,\ Input\ Ground\ Motion). \tag{2}$$

The output of the identification function shows, for the example, the level of aging degradation or damage caused by previous earthquakes in building structures and thus can be utilized for estimation of refurbishment necessity. As inputs of the identification function, the monitored data obtained by IoT-HUB can be utilized but they are measured with various types of sensors and therefore do not have the same level of accuracy. This fact makes it essential to understand what kind of information can be extract from each sensor data for keeping information reliability. For this purpose, calibration, validation and benchmarking of those monitored data become necessary by using well-defined reference data from experiments or equivalent simulations. As one option, the archive of experimental data obtained by using the NIED-operated large scale shaking table or *E-defense* named “Archive of Shaking table Experimentation dataBase and Information (ASEBI)” [10] can be utilized. To solve Eq.(2), recent studies in statistical machine leaning propose various types of methods for change and anomaly detection [11] can be used. Also, system identification methods are proposed for determining structural parameters [12]. Developing and applying these non-parametric machine learning and parametric system identification is another challenge in the proposed urban CPS.

### 4.3 Use cases

The operation concept of the urban CPS will be described by using “Use cases” in this section. Here, how actors utilize the urban CPS will be analyzed. The urban CPS is a dynamic system that needs to be always updated and maintained so that the urban community model is fitted reflecting changes of the community and monitored data such as vibration. In addition, the simulation techniques are improved using cutting-edge technologies, newly-developed earthquake-disaster-mitigation method are numerically modeled and introduced in the urban community model library of Information platform and the numerical structural models are modified by utilizing actual earthquake response of structures. To make this dynamic system active, the urban CPS must be operated as an ecosystem, which will be also discussed in the next section.



 

The actors on the urban CPS can be categorized into "*Users*," "*Operators*," or "*Developers*." At first, the profiles of the three actors will be described. The *users* of the system are expected to spread in the various fields of the community, such as individual citizens, private companies or local and national governments. The *operators* who manage the urban CPS must be not a private company but a certain public organization, at least in the early stage, because the CPS collects and utilizes urban model data owned by various entities. It is necessary for such public organizations to develop a CPS prototype, to start to operate the prototype with private companies, local governments and individual citizens who are interested in the CPS as *users*, and to show benefits of utilizing the system to the society. After the operation is matured and expanded so that the operation becomes difficult for the public organization, it might be better to restructure the operation scheme into business operation including services using the CPS and the system maintenance. The *developers* may be researchers in public research institutes, universities or private companies who are interested in earthquake engineering and information technology. It is desirable for the *operator*s to construct research structure in which the *developers* can work together under the same vision for developing and improving the CPS.

The *users* can utilize the urban CPS for understanding the capability of structures, predicting earthquake disasters in an area or a city and evaluating the effect of earthquake countermeasures quantitatively and thus can promote appropriate actions for enhancing earthquake resistance. As an individual use, for example, a resident could receive seismic resistance diagnosis without paying much fee by using the proposed system and monitored vibration data. It is expected that this encourages the introduction of earthquake-disaster-mitigation measures. On the other hand, for public use, local governments can make effective disaster-mitigation policies by using disaster prediction. For this purpose, it is important to define essential factors for keeping community functions under natural disaster occurrence such as earthquakes. Private enterprises can take various advantages from the urban CPS, one of which is making a decision of a large size of business investment based on the evaluation of city-level disaster mitigation capabilities and their economic effects. In addition to the enhancement of readiness as discussed above, the urban CPS can be used for making proper reaction when earthquake hazards occurred. For example, the urban CPS can provide national and local governments with useful information to help decision-makings on disaster reaction and support to business continuities of private enterprises because it can predict places and levels of damages under disasters by continuously monitoring data.

The *operators* work for system management and provide with services in operation of the urban CPS. The system management includes registration and administration of continuously updated urban community model and monitored data, installation of developed simulation tools for prediction and evaluation calculations and preparation of constitutive model of newly developed earthquake-disaster-mitigation measures. The service includes the development of user interface applications for users to obtain necessary data (such as Graphical User Interface (GUI)) and the management of user accounts.

The *developers* promote R&D to enhance the capability of prediction and evaluation functions in Simulation platform and the accuracy of quantitative output from such calculations using the collected and unified BIM/CIM data, statistical information and monitored structural responses. Since the urban CPS consists of technologies from various science and engineering fields, contributions of various types of *developers* are expected. Some of them are as follows: Researchers in computational engineering develop new simulation methods and make their V&V (Verification and Validation). Those in earthquake engineering develop new earthquake-disaster-mitigation measures and provide with their numerical model to the urban CPS. Those from information technology develop sensing data management for making collecting and managing data effectively.

### 4.4 Eco-system

"Eco-system" is a figurative expression to describe relationship of entities in social systems including economic interdependency and cooperation. An innovative idea cannot be adapted to social systems by itself but needs to utilize other complemental ideas and to establish process for delivering values to final users with partners [13]. Therefore, the construction of the urban CPS is not sufficient for its continuous and effective operation. The three actors in the urban CPS operation, that is, the *users*, the *operators* and the *developers* are expected to work for utilization, operation and enhancement of the urban CPS in their own roles and take advantage of the CPS for urban design that strengthens the resilience of urban communities.

The *users* need not only to evaluate earthquake resilience but also to create benefit from the evaluation. When the *users* (individual citizens, private entities or local governments) study their disaster-mitigation-related investments or policies, they can take the most profitable approach if quantitative comparison between necessary cost of an disaster-mitigation measure and present value of obtained benefit by reduction of probability and seriousness of possible damages becomes possible. Also, the benefit of the earthquake-disaster-mitigation measures shown by the CPS could be reflected on the price of real estates. This is another way to create values from the urban CPS.

The *operators* would collect monitored data of sensor-networks operated for other purposes from their owners for the CPS operation. To make it possible, the operators need to show the purpose of the CPS clearly so that the owners agree to join the process. Therefore, they are required to organize a contract on intellectual property rights of the data to be collected under the consideration of conflicts in stakeholders. Another necessary condition is that the *operators* need to construct the system in which BIM/CIM data are provided to the CPS when they are updated. Operation including the above-mentioned activities requires a certain amount of budget. Since making earthquake-resilient city is the purpose of the urban CPS, as described in the previous section, it may be appropriate for the system at the early stage to get started and be operated by an organization in the public domain. However, for continuous and sustainable operation of the CPS, it is expected that the CPS operation body in public domain will transition into a stand-alone-basis organization under the income from fee in utilization of the CPS.

The *developers* continue to contribute to enhancement of functions by using the CPS resources as a R&D platform. Although the CPS would be constructed with available technologies at the time of start, it is required to add supplemental functions to meet new needs of the *users* and to reflect newly-found facts from earthquake experiences. Some of them are more precise predictive simulation, user-friendly simulation interface, and innovative disaster-mitigation measures.

## 5. Conclusion

A framework that makes adaptation of earthquake-disaster-mitigation measures easier and thus urban communities more earthquake-resilient was proposed and its concept was described. This framework consists of two elements; one is a certification process of earthquake-disaster-mitigation measures and the other is “urban cyber-physical system (CPS)” that could evaluate earthquake-resistant capability of buildings and/or social infrastructure.

In the certification process, a newly-developed earthquake-mitigation measure would be reviewed and then certified when its effect satisfies a predetermined standard. This certification is expected to give proper information of the measure in quality to owners of buildings and/or infrastructures for making their decisions.

The urban CPS would have Information platform that is a numerical model database of buildings and/or infrastructure in a considered urban community and Simulation platform that is a computational simulation resource. The CPS output of quantitative effect evaluation of the measures is expected for the owners to understand the cost-effectiveness of the installation of the measures. To construct the CPS, the followings are needed: (1) Construction and continuous update of Information platform through data aggregation and analysis of existing vibration data of structures, BIM/CIM data sets and other various available databases, and (2) Development of Simulation platform that has two functions; a prediction function to calculate behaviors of urban communities and infrastructures during earthquakes by using the data in Information platform and an identification function to identify the structural system from the relation between input earthquake motions and responses of the structure. In addition, the eco-system that is required to operate, continue and develop was also discussed.



 

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