DOI: http://dx.doi.org/10.13161/kibim.2015.5.4.037

Web-based Collaboration Systems for Structural Design: A Review

Lim, Jinkang[1] · Lee, Jaewook[2] · Lee, Seunghye[3] · Kim, Han Soo[4] · Jung, Sungwon[5]

Received December 2, 2015 / Accepted December 18, 2015

ABSTRACT: In a construction project, collaboration amongst the project participants is a critical factor for high-quality results and successful completion of the project. Owing to the advance of information technologies, web-based systems have become more common in the construction industry, but research and development has been made for only limited areas. For organized and systematic collaboration in various fields, collaboration systems have to be developed in a holistic manner based on diverse needs from the whole construction industry. This study aims to investigate the current status of web-based collaboration systems from structural engineers' perspectives and propose an improvement plan. For a systematic analysis of selected cases, we apply a classification of three developmental stages depending on interoperability and organizational levels: structural design and analysis, collaborative design, and integrated design management. Thereafter, the characteristics of each stage are extracted and comparatively analyzed. Lastly, three functional factors were proposed for the improvement of web-based collaboration systems for structural design.

KEYWORDS: Web-based Collaboration System, Structural Design, Design Collaboration, Interoperability, Classification System

1. Introduction

The construction process is composed of a series of complicated activities in which experts from diverse backgrounds participate, and project participants share a vast amount of diverse information for the completion of the project. Such information becomes a medium for collaboration within a field or between different fields. Collaboration is defined as "more durable and pervasive relationships that create new structures with shared goals to achieve mutual benefit" (Mattessich and Monsey, 1992) offering each organization an opportunity to perform individual works and reduce problems caused by a lack of communication (Hong et al., 2004). However, the conventional paper-based communication methodology has limitations in carrying out the collaboration as a more systematic relationship, not just a co-work one.

For the past decade, the sharp growth of information and communication technologies has had a significant effect on the AEC (Architecture, Engineering and Construction) industry. In particular, the dramatic development of Internet technology has made systematic collaboration possible in construction projects (Xue et al., 2012). Specifically, the development of web-based computer applications has been active to overcome temporal and spatial constraints during the collaborative construction process (Woo, 2007). Web-based systems have provided cyberspace for various activities such as generation, exchange, review and discussion of information. This kind of web-based collaboration has a positive effect on work performance in design and engineering companies (Nitithamyong and Skibniewski, 2004).

The type of computer software can be divided into three categories: PC-standalone, Internet-based, and web-based software (Weng, 2011). Among them, the web-based software neither requires individual installation of software nor reinstallation of existing software due to repair or replacement

[1]학생회원, 세종대학교 건축공학과 석사과정 (jwlsrkd@naver.com)
[2]정회원, 세종대학교 건축공학과 교수 (jaewook@sejong.ac.kr)
[3]비회원, 세종대학교 건축공학과 박사후연구원 (lsh2002437@gmail.com)
[4]비회원, 세종대학교 건축학과 교수 (hskim@sejong.ac.kr)
[5]비회원, 세종대학교 건축학과 교수 (swjung@sejong.ac.kr) (교신저자)

of the computer. Moreover, software maintenance and upgrades are done on the web server. Due to these advantages of web-based systems, various commercial software applications for construction projects have started to provide online services (Nitithamyong and Skibniewski, 2004). The use of web-based collaboration systems in the construction industry will be further accelerated based on data accessibility, availability and timeliness (Rojas and Songer, 1999).

To promote a construction project properly, information exchange among project participants (e.g., client, architect, structural engineer, mechanical engineer, contractor, facility manager, etc.) is required.

In particular, it is essential to minimize communication problems among them and reduce design errors during the design process for the successful implementation of the project (Chen et al., 2005). Even when the design itself were zero-defect, redesign would always take place due to the client's requests or other changes in various reasons. In general, design changes frequently occur during the design phases such as schematic design, design development, and construction document causing cost increases and schedule delays. Under these circumstances, the role of structural engineers is very important. The completion of structural design is the stage to determine structural members which affect architecture, civil engineering, MEP (Mechanical, Electrical, and Plumbing), and finishing. In fact, it is a critical process to reflect all design information and eliminate errors. Considering this aspect, the web-based collaboration system offers many advantages to structural engineers. However, studies on web-based systems in the construction sector mostly cover construction information management (Chassiakos and Sakellaropoulos, 2008), subcontractor selection (Arslan et al., 2008), design management (Senthilkumar et al., 2010) and project monitoring (Cheung et al., 2004). Therefore, not much studies have done related to structural design.

A web-based collaboration system for a construction project should meet the requirements from diverse fields, not just the functions for a specific field only. However, conventional collaboration systems have limitations in providing efficient collaboration support because the requirements of structural design have not been properly reflected. For the systematic development of web-based systems to better support collaboration, this study reviews current web-based systems from the standpoint of structural design, and proposes functional factors for the system improvement.

This paper is structured as follows: Section 2 describes a classification system for the analysis of web-based system cases, Section 3 presents the result of the case analysis and the characteristics of the current systems, Section 4 proposes functional factors to be considered for the improvement of web-based collaboration systems for structural design, and Section 5 concludes the study by discussing its significance and future directions.

2. Development of Classification System for Case Analysis

2.1 Analysis of Conventional Classification Systems

To build a classification system for case analysis, we have investigated several classification systems related to collaboration (Boddy et al., 2007, Horvath, 2012, Steel et al., 2012, Xue et al., 2012). Each classification system includes a set of different categories depending on its topic (Table 1). Among them, the studies by Horvath (2012) and Boddy

Table 1 Classification systems

Study	Steel et al., 2012	Xue et al., 2012	Horvath, 2012	Boddy et al., 2007
Subject	Model interoperability	IT supported collaborative work	Computer supported cooperative work	Computer integrated construction
Classification Criteria	Interoperability	Organization & Technology	Integration	Semantics & Application
Classification Groups	4 Levels	3 Stages	4 Levels	4 Areas
Group Details	1: File 2: Syntax 3: Visualization 4: Semantics	1: Collaborative design 2: CCPM 3: IIMIS	1: Cooperation 2: Coordination 3: Collaboration 4: Coadunation	1: Data-application 2: Application-semantics 3: Data-process 4: Process-semantic

Table 2 The KISS classification of interoperability levels (Steel et al., 2010)

Category	Level 1	Level 2	Level 3	Level 4
Artifact	Persisted source	Syntax tree	Model instances, Source code	Running code
Level	File	Syntax	Visualization	Semantics
Created by	Writer tool	Reader tool, Editor	Editor	Compiler, Interpreter
Consumed by	Reader tool	Writer tool	Human	Platform

Table 3 Classification system with three stages according to the application of IT (Xue et al., 2012)

Low Level ← Organizational Level → High Level		
Collaborative Design	CCPM (Collaborative Construction Projects Management)	IIMIS (Integrated Inter-organizational Management Information Systems)

et al. (2007) are inappropriate in classifying collaboration systems to be analyzed in this study because they analyzed cases through the integration level of cooperative work, semantic, and application. For this study, we developed a classification system by referring to the study by Steel et al. (2012) that analyzes design software depending on interoperability level and the study by Xue et al. (2012) that examines applications of information technology depending on organizational level.

Steel et al. (2012) emphasizes the importance of securing interoperability through the IFC (Industry Foundation Classes) format amongst diverse BIM software. In this study, interoperability levels are classified into file level, syntax level, visualization level and semantic level in accordance with the Knowledge Industry Survival Strategy (KISS) Classification (Table 2).

Xue et al. (2012) investigated studies of the past decade in order to determine the effects of information technologies on collaborative works on AEC projects. They classified the study cases into three stages depending on the organizational level of information technologies (Table 3). Then, they analyzed how the application of information technologies has evolved for collaboration among project participants. According to the analysis, information exchange and quick decision-making have become more important for collaboration amongst project participants as buildings become larger and more complex.

In the aforementioned two studies, by analyzing study cases based on a classification system, an improvement plan is proposed. In this study as well, to classify web-based collaboration systems for structural design, we have developed a 3-stage classification system by combing the two classification systems above.

2.2 Development of Classification System

For case analysis, we define three classification stages (i.e., Structural Design and Analysis, Collaborative Design, and Integrated Design Management) depending on interoperability and organizational level as shown in Figure 1. In the first stage, 'Structural Design and Analysis,' pre/post-processing is enabled for structural analysis in the web-based system. Most cases (Weng, 2011, Marante et al., 2005, Chen et al., 2006, Yang and Elgamal, 2004, Nuggehally et al., 2003) in this stage include graphical visualization functions for the accurate analysis of structures. Some cases (Yang and Elgamal, 2004, Nuggehally et al., 2003) deals with issues of information storage and security.

The second classification stage is 'Collaborative Design' in which communication and data exchange functions are added for collaboration between participants. These functions make it possible to solve temporal and spatial problems which frequently occur during joint task operations. In addition, structural engineers are able to make quick decisions through communication with other participants

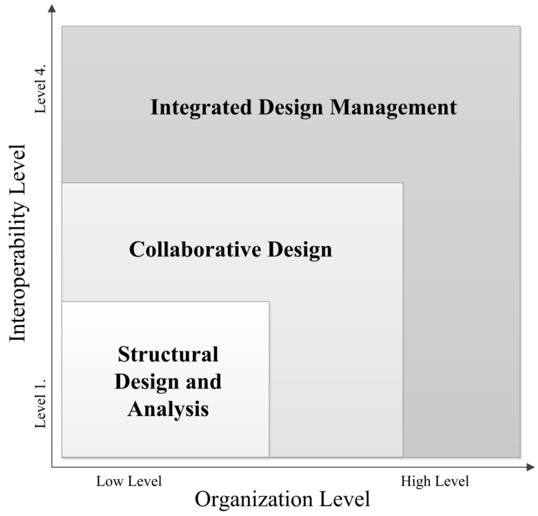

Figure 1 Classification system according to level of collaboration

during member design and correction based on the structural analysis data.

The third stage, 'Integrated Design Management,' includes the management functions needed to carry out the project. In general, the web-based collaboration system of the third stage provides functions for integrated project management including schedule management, opinion exchange, job allocation, user management, and cost management as well as functions of the first and second stage.

For case analysis, first, major functions of each classification stage are extracted. In structural design, the core task using the web-based system is structural analysis. As described above, the cases in which basic structural analysis and pre/post-processing are major functions are categorized as 'Structural Design and Analysis.' The cases with the functions needed for communication and data exchange between design participants are classified as 'Collaborative Design.' The cases under 'Integrated Design Management' provide a series of functions for efficient project management such as workflow management and cost management. Although diverse characteristics are found in each system case, this study primarily analyzes major functions, and the results are summarized in Table 4.

In structural design through web-based collaboration, there must be results of the structural analysis. After visualizing and schematizing them on the web-based system, then, the understanding of structure and opinion exchange can be further accelerated. Unlike the construction process which changes depending on site conditions, because most structural design tasks are executed using software, opinions can be efficiently exchanged through email or video conferencing. In addition to structural design tasks, workflow and cost management functions support management tasks for performing a design project.

Table 4 Major functions by classification

Classification	Major functions
Structural Design and Analysis	· Structural design · Structural analysis · Data visualization · Pre/Post processing
Collaborative Design	· Structural design · Structural analysis · Data visualization · Pre/Post processing + · Communication function · Data exchange
Integrated Design Management	· Structural design · Structural analysis · Data visualization · Pre/Post processing + · Communication function · Data exchange + · Workflow management · Cost management

3. Case Analysis of Web-based System

3.1 Structural Design and Analysis

The cases categorized as 'Structural Design and Analysis' enable data generation for structural analysis and provide diverse functions for pre/post-processing of the data on the web-based system. Each case provides different structural analysis and visualization functions according to its purpose (Figure 2).

WebDFEA (Weng, 2011), a web-based system for Finite Element Analysis (FEA), uses ANSYS to generate data for structural analysis. In this system, design results are analyzed dynamically and statically through post processing, and the analysis results are visualized in 3D using an OpenGL API (Application Programming Interface). The system is connected to both web server and database server using a browser for data transmission and storage.

In other system cases, both pre- and post-processing functions are available. Portal of Damage (Marante et al., 2005), a web-based nonlinear dynamic analysis system, offers analysis functions for reinforced concrete structures on a web server. The primary purpose of this system is to interpret the reinforced concrete structure under overload which may cause serious damage to the structure. With the analysis results, it is possible to check damage behavior of the crack. Through the system, both input and output data on structural analysis can be printed in text format, and pre/post-processing can be visualized.

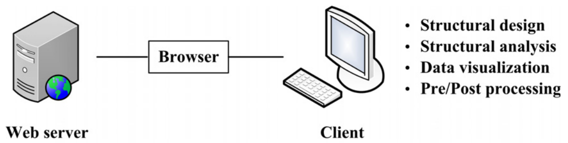

Figure 2 Structural design and analysis

There are systems with additional functions other than structural analysis. Chen et al. (2006) suggest a prototype of web-based structural engineering for seismic assessment on a bridge. This system consists of a user unit, administration unit, and application program unit. Through the application program unit, multiple users can collaborate with each other at the same time. The structural analysis module included in the application program is updated and maintained to be a latest version by the administration unit. The administration unit also handles web server management, schedule management, and security management as well as the management of the application program unit.

Some other cases analyze seismic response through simulation. Yang and Elgamal (2004) developed a web-based system which performs structural analysis based on model data and soil condition data, and provides the results in graphic or text format. Through this case, they point out a security problem of the web-based system. To solve the security problem, they proposed an IP address-based login method and a virus scan for uploaded files. Nuggehally et al. (2003) also mention a security problem in their web-based system for BEM (Boundary Element Method) analysis. As a solution to this problem, they suggested removal of local hard disks, installation of a policy file or use of commercial security certificate service.

3.2 Collaborative Design

We analyzed the cases under 'Collaborative Design' focusing on the opinion and data exchange functions for multiple design participants. The design participants perform structural design and analysis through a web server, and share opinions and data with each other (Figure 3). The opinion exchange function has been diversely used from simple post-it to video conferencing. For data exchange, in addition to simple file exchange, visualization data or files are exchanged to assist participants' tasks.

A system proposed by Chen et al. (2005) offers functions for review and feedback reporting process which are repeated during the design process. This system improves interoperability between different software applications using the IFC format, a standard BIM (Building Information Modeling) format. There are also some cases in which different standard data formats are used. Peng et al. (2003) proposed a FEA-based collaboration system which performs structural analysis by creating an object-oriented model based on matrices and vectors. Then the analysis results are represented using XML (eXtensible Markup Language). In another web-based system by Lee and Jeong (2006), ISO 10303 standard model is used for the design of steel bridges. This system allows implementation of a steel bridge model in 3D and input of structural analysis and design data.

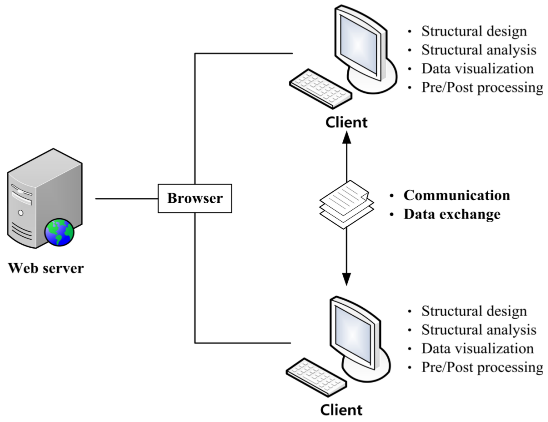

Figure 3 Collaborative design

In a web-based system by Peng and Law (2002) for 2D nonlinear dynamic structural analysis, standard design data are shared through a communication channel between the server and client systems for efficient collaboration. This system, by modularizing analysis tools, allows the user to select an analysis tool and change it to another one if necessary. This method is useful in that it can enhance the user's convenience and workability when the web-based collaboration system becomes larger.

Chen and Lin (2011) propose an Internet-based computing framework which can simulate the multi-scale responses of a structural system. To overcome the weakness of conventional Internet technologies, they utilize an inter-cluster distributed computing environment and multi-level hierarchical modeling and simulation. Moreover, an inter-cluster communication protocol is applied for smooth communication among project participants. A similar approach is found in an object communication model proposed by Abdalla (2006).

3.3 Integrated Design Management

The cases under 'Integrated Design Management' offer

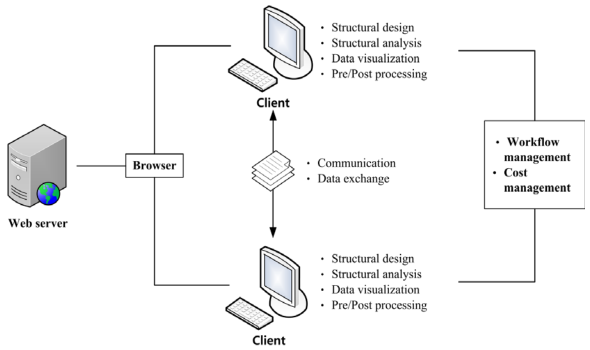

Figure 4 Integrated design management

workflow and cost management functions for overall design project management including the functions from the previous two stages (Figure 4).

e-Engineering Hub by Ren et al. (2008a) is a standardized collaboration platform for engineering outsourcing. This system consists of five modules: User Management, Communication Management, Document Management, Project Plan and Workflow Management. First, engineering tasks are fulfilled using individual modules. Based on the results, then, the information on the size and quality of structural member is output. Next, actual price and purchase information on the member is provided through the web system. That is, the members which do not meet price levels and purchase conditions are redesigned to reduce overall construction costs. Ren et al. (2006) also suggest tools which can be used in the engineering web service through a case study on e-Engineering Hub. They mention a total of 6 service categories (i.e., general communication, data exchange, collaboration, data storage, legal matters, and knowledge search) and list functions for each category.

Leon and Laing (2013) propose principles and protocols to support multidisciplinary collaborative design in an early stage through visual and tactile user interfaces. In this study, an optimum design process is presented based on the principles and protocols to promote collaboration in the conceptual design stage.

Eynard et al. (2005) introduce three domains for the development of a collaboration system: analysis domain, database domain, and user domain, and provide various functions for teamwork including opinion exchange, project and document management, and job management. Another web-based FEM system, Web-FEM (Chen and Lin, 2008) provides high-performance structure analysis services for users through just web access. This system adopts an object-oriented FEA program and has diverse features such as 3D graphics, multi-user management, and fault tolerance.

3.4 Results of Case Analysis

Table 5 summarizes the results of the case analysis including the case classification and the functions of the three stages. Based on the analysis results, this section discusses the status and problems of the current web-based collaboration system.

The cases under 'Structural Design and Analysis' basically offer a structural analysis function and other functions including a visualization function. Visualization is an essential function to share analysis results and discuss problems among project participants. Additional functions for data storage and security target to minimize problems during collaboration.

The cases under 'Collaborative Design' provide functions from 'Structural Design and Analysis' and, at the same time, communication and data exchange functions. With these additional functions, participants can have a better understanding of the project and accelerate the process through accurate communication. If the collaboration process is prolonged and complicated, communication and data exchange processes for decision-making become more important.

In the cases above, the advantages of the web are mostly introduced to enhance structural design and collaboration processes. However, 'Integrated Design Management' aims to manage the overall structural design process in an integrated manner. For this, project management functions such as workflow management and cost management are provided. As shown in Table 5, however, it is still relatively difficult to find studies and actual system cases in this stage. In particular, cost management functions have not been properly implemented throughout the structural design process. As the number of project participants increases, the collaboration-based integrated project management becomes more important.

Other studies (Tann and Shaw, 2007, Ren et al., 2008b, Lee and Jeong, 2012, Shen et al., 2010, Deng and Chang,

2006) discuss the necessity of a standard data model for interoperability, communication and decision-making problems which occur due to specialty differences, and cost management matters to reduce the cost of large projects.

4. Proposal of Functional Factors

Recently, construction structures have gradually become large, and structural systems have become more diverse and complicated. Therefore, there should be efforts to minimize errors which can occur during collaborative design and improve the feedback process on design results. This study proposes functional factors to be added or improved for the development of a web-based collaboration system based on the case analysis results as follows:

- Application of a standard data model
- Quantification of design variables
- Development of economic evaluation functions

First, interoperability should be secured through the use of a standard data model which is a commercially neutral format. Considering that the entire construction process is based on information, this would be the most effective method to solve compatibility problems (Lee, 2012). Because revision or redesign during structural design are usually done through a feedback process with other participants, compatibility problems often take place due to the use of different software. Therefore, if interoperability is secured with a standard data model, opinion exchange and review could be carried out effectively, which would in turn reduce design errors and improve design quality.

As shown in Table 5, the major duty on the web-based collaboration system is structural analysis. The program used for this work has fast evolved and been upgraded in a rapid cycle along with the advance of information and communication technologies. The use of a standard information model during the structural design can minimize diverse problems caused by the frequent change of software. In fact, advantages of a standard data model are discussed in more than half of the study cases (Chen et al., 2005, Peng et al., 2003, Lee and Jeong, 2006, Peng and Law, 2002, Eynard et al., 2005, Chen and Lin, 2008, Huang, 2002). If the IFC format, one of standard data models, is applied,

Table 5 Analysis of major system functions

Classification System		Integrated design management						
		Collaborative Design						
		Structural design and analysis						
	Major Functions / Research Cases	Structural design & analysis	Data visualization	Pre/Post processing	Communication function	Data exchange	Workflow management	Cost management
Structural Design and Analysis	Weng, 2011	○	○	○	N/A	N/A	N/A	N/A
	Marante et al., 2005	○	○	○	N/A	N/A	N/A	N/A
	Chen et al. 2006	○	○	○	N/A	N/A	○	N/A
	Yang and Elgamal, 2004	○	○	○	N/A	N/A	N/A	N/A
	Nuggehally et al., 2003	○	○	○	N/A	N/A	N/A	N/A
Collaborative Design	Chen et al., 2005	○	N/A	N/A	○	○	N/A	N/A
	Peng et al., 2003	○	○	○	N/A	○	N/A	N/A
	Lee and Jeong, 2006	○	○	N/A	N/A	○	N/A	N/A
	Peng and Law, 2002	○	○	○	○	○	N/A	N/A
	Chen and Lin, 2011	○	○	○	○	N/A	N/A	N/A
	Abdalla, 2006	○	○	○	○	○	N/A	N/A
Integrated Design Management	Ren et al., 2008a	○	△	△	○	N/A	○	○
	Ren et al., 2006	○	△	△	○	N/A	○	N/A
	Leon and Laing, 2013	○	○	N/A	○	N/A	△	△
	Eynard et al., 2005	○	○	○	○	○	○	N/A
	Chen and Lin, 2008	○	○	○	○	○	○	N/A

however, data loss may occur due to different IFC versions or differences in the data exchange method. For CIS/2 (CIMSteel Integration Standard), another standard data model, it has a limited application to steel structure design. Therefore, there should be further studies on how to increase the use of a standard data model throughout the structural design process.

Second, to consider all possible design variables, there should be diversification and quantification of design variables. Since decision-making for structural design cannot be easily represented in a mathematical expression, it is closely related to objective functions or constraints which are excluded from an optimization model (Choi, 2007). As shown in Table 5, however, the cases on the web-based collaboration systems for conventional structural analysis are poor at considering these design variables so that the focus is on structural analysis and data processing. Sometimes, the objective functions which do not work as the variables of structural design because of the absence of quantification can have a significant effect on optimization design. When the structural design is carried out on the web-based system, therefore, it is critical to quantify all variables and constraints, which are generally considered in the offline stage, in the online environment. Quantified variables and constrains can be used as a medium for opinion exchange through visualization or suggest an optimal design alternative.

Third, it is necessary to develop the function which can evaluate the economic efficiency of design results. Recently, interest in construction costs has shifted from initial construction cost to maintenance cost (Kim et al., 2008). In fact, it has become more common to apply the evaluation on life cycle cost to the cost estimation of a construction project. As a strategy to strengthen construction companies' competitiveness, pre-construction services, which provide optimum technology, estimation of construction period, optimal budget and cost reduction plans during the design process, have become more important (Byun and Kim, 2012).

As a construction project becomes larger, structural member cost has a bigger effect on total construction cost. The selection of structural members (e.g., reinforced concrete structure, steel-frame structure, etc.) is determined during economic evaluation. If this economic evaluation is available from the initial structural design stage, review and revision processes could be shortened.

Some of the studies (Ren et al., 2008a, Leon and Laing, 2013) provide price information on structural members on a real-time basis or manage costs relating to changes in structural design in the initial design stage. However, it is difficult to find studies on the cost management of structural members throughout the whole design process. If it is possible to estimate unit price by material, predict construction costs considering life cycle costs on the selected materials and compare prices on alternative design on the web-based collaboration system, collaboration among project participants and their decision-making would be further benefited.

In addition to the technologies and functions mentioned in this study, there could be more factors added to the web-based system with the growth and advance of information and communication technologies. Therefore, an expansion should be considered from the system development stage.

5. Conclusion

This study analyzed the current status of web-based collaboration systems from the perspective of structural design and proposed functional factors that should be added or improved. A web-based system has many advantages for a construction project in three aspects: accessibility, availability and timeliness. In particular, it is a highly useful tool during collaboration for structural design. Though the system is still lacks compared to those of other sectors such as architecture and MEP design, there have been diverse R&D activities for structural design.

In this study, we developed a classification system depending on interoperability and organizational levels, classified cases into three stages, and analyzed functions by stage. Through the case analysis, as functional factors for the improvement of the web-based collaboration system, we proposed 'application of a standard data model,' 'quantification of design variables' and 'development of economic evaluation functions.' During the structural design with a web-based collaboration system, if the proposed functional factors are implemented along with basic functions from the stages, it would be possible to provide more practical services to enhance design quality and productivity.

Acknowledgments

This work was supported by grants funded by the Ministry of Land, Infrastructure and Transport (13AUDP–C067836–01), and by the National Research Foundation (NRF) (No. 2013 R1A2A2A01005721, 2014R1A2A1A11051772) of the Korean government (MSIP).

References

Abdalla, J. A. (2006), "A communication model for structural design objects", Ⅰ: Channels and medium. Advances in Engineering Software, Vol. 37 No. 6, pp. 382–392.

Arslan, G., Kivrak, S., Birgonul, M. T. and Dikmen, I. (2008), "Improving sub–contractor selection process in construction projects", Web–based sub–contractor evaluation system (WEBSES). Automation in Construction, Vol. 17 No. 7, pp. 480–488.

Boddy, S., Rezgui, Y., Cooper, G. and Wetherill, M. (2007), "Computer integrated construction: A review and proposals for future direction", Journal of Advanced in Engineering Software, Vol. 38 No. 10, pp. 677–687.

Byun, I. and Kim, Y. (2012), "An analysis of core competence of Pre–construction Service of the making inroads into oversea construction market", Korean Journal of Con–struction Engineering and Management, Vol. 13 No. 2, pp. 80–90.

Chassiakos, A. P. and Sakellaropoulos, S. P. (2008), "A web–based system for managing construction information", Advances in Engineering Software, Vol. 39 No. 11, pp. 865–876.

Chen, H. M., Lin, Y. C. and Chao, Y. F. (2006), "Application of web services for structural engineering systems", Journal of computing in civil engineering at ASCE, Vol. 20 No. 3, pp. 154–164.

Chen, H. M. and Lin, Y. C. (2008), "Web–FEM: An internet–based finite–element analysis framework with 3D graphics and parallel computing environment", Journal of Advances in Engineering Software, Vol. 39 No. 1, pp. 55–68.

Chen, H. M. and Lin, Y. C. (2011), "An Internet–based computing Framework for the simulation of multi–scale response of structural systems", Structural Engineering and Mechanics, Vol. 37 No. 1, pp. 17–37.

Chen, P. H., Cui, L. C., Wan, C., Yang, Q., Ting, S. K. and Tiong, R. L. K. (2005), "Implementation of IFC–based web server for collaborative building design between architects and structural engineers", Journal of Automation in Construction, Vol. 14 No. 1, pp. 115–128.

Cheung, S. O., Suen, H. C. H. and Cheung, K. K. W. (2004), "PPMS: a Web–based construction Project Performance Monitoring System", Automation in Construction, Vol. 13 No. 3, pp. 361–376.

Choi, B. H. (2007), "Development of Decision Support System for the Design of Steel Frame Structure", Journal of Korean Society of Steel Construction, Vol. 19 No. 1, pp. 29–41.

Deng, X. Y. and Chang, T. Y. P. (2006), "Creating Structural Model From IFC–Based Architectural Model", Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montreal.

Eynard, B., Li nard, S., Charles, S. and Odin, A. (2005), "Web–based collaborative engineering support system: Applications in Mechanical design and structural analysis", Journal of Concurrent Engineering, Vol. 13 No. 2, pp. 145–153.

Hong, S. G., Kim, N. H. and Youn, K. A. (2004), "Development Web–based Design Tool for Gravity System Design of a Tall Building", Proceeding of Architectural Institute of Korea, Vol. 24 No. 2, pp. 223–226.

Horvath, I. (2012), "Recent developments in computer supported cooperative work in design: From group collaboration through global connectivity to informing apobetics", Computer Supported Cooperative Work in Design, pp. 2–13.

Huang, G. Q. (2002), "Web–based support for collaborative product design review", Computers in Industry, Vol. 48 No. 1, pp. 71–88.

Kim, T. H., Gu, B. H., Kim, O. G., Park, T. G. and Lee, H. S. (2008), "The Development of Life Cycle Cost Evaluation Index for Public Facilities", Korean journal of Construction Engineering and Management, Vol. 9 No. 6, pp. 216–224.

Lee, G. (2012), "BIM data exchange and standard between software", Korean journal of Construction Engineering and Management, Vol. 13 No. 3, pp. 15–18.

Lee, J. W. and Jeong, Y. W. (2012), "User–centric knowledge representations based on ontology for AEC design collaboration", Computer-Aided Design, Vol. 44 No. 8, pp. 735-748.

Lee, S. H. and Jeong, Y. S. (2006), "A system integration framework through development of ISO 10303-based product model for steel bridges", Journal of Automation in Construction, Vol. 15 No. 2, pp. 212-228.

Leon, M. and Laing, R. (2013), "Towards a Computer Mediated Methodology for Collaborative Design during the Early Architectural Design Stages", Proceedings of the 2013 IEEE 17th International Conference on Computer Supported Cooperative Work in Design, pp. 489-495.

Marante, M. E., Su rez, L., Quero, A., Redondo, J., Vera B., Uzcategui, M., Delgado, S., Le n, L. R., Núñez, L. and Flórez-López, J. (2005), "Portal of damage: a web-based finite element program for the analysis of framed structures subjected to overloads", Journal of Advanced in Engineering Software, Vol. 36 No. 5, pp. 346-358.

Mattessich, P. W. and Monsey, B. R. (1992), "Collaboration-What makes it work: A review of research literature on factors influencing", Amherst H. Wilder Foundation.

Nitithamyong, P. and Skibniewski, M. J. (2004), "Web-based construction project management systems: how to make them successful?", Journal of Automation in Construction, Vol. 13 No. 4, pp. 491-506.

Nuggenhally, M., Liu, Y. J., Chaudhari, S. B. and Thampi, P. (2003), "An internet-based computing platform for the boundary element method", Journal of advances in engineering software, Vol. 34 No. 5, pp. 261-269.

Peng, J. and Law, K. H. (2002), "A prototype software framework for internet-enabled collaborative development of a structural analysis program", Journal of Engineering with Computers, Vol. 18 No. 1, pp. 38-49.

Peng, J., Liu, D. and Law, K. H. (2003), "An engineering data access system for a finite element program", Journal of Advances in Engineering Software, Vol. 34 No. 3, pp. 163-181.

Ren, Z., Anumba, C. J., Hassan, T. M., Augenbroe, G. and Mangini, M. (2006), "Collaborative project planning: a case study of seismic risk analysis using an e-engineering hub", Journal of Computers in Industry, Vol. 57 No. 3, pp. 218-230.

Ren, Z., Anumba, C. J., Augenbroe, G. and Hassan, T. M. (2008a), "A functional architecture for an e-Engineering hub", Journal of Automation in Construction, Vol. 17 No. 8, pp. 930-939.

Ren, Z., Hassan, T. M. and Anumba, C. J. (2008b), "The engineering services of a universal e-Engineering Hub: Application to the construction industry", Advances in Engineering Software, Vol. 39 No. 7, pp. 545-557.

Rojas, E. M. and Songer, A. D. (1999), "Web-centric systems: a new paradigm for collaboration engineering", Journal of Management in Engineering, Vol. 15 No. 1, pp. 39-45.

Senthilkumar, V., Varghese, K. and Chandran, A. (2010), "A web-based system for design interface management of construction projects", Automation in Construction, Vol. 19 No. 2, pp. 197-212.

Shen, W., Hao, Q., Mak, H., Neelamkavil, J., Xie, H., Dickinson, J., Thomas, R., Pardasani, A. and Xue, H. (2010), "Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review", Advanced Engineering Informatics, Vol. 24 No. 20, pp. 196-207.

Steel, J., Drogemeuller, R. and Toth, B. (2012), "Model interoperability in building information modeling", Software & System Modeling, Vol. 11 No. 1, pp. 99-109.

Tann, W. and Shaw, H. J. (2007) "The collaboration modeling framework for ship structural design", Ocean Engineering, Vol. 34, pp. 917-929.

Weng, W. C. (2011) "Web-based post-processing visualization system for finite element analysis", Journal of Advances in Engineering Software, Vol. 42 No. 6, pp. 398-407.

Woo, S. J. (2007) "A Study of the Knowledge-based System Model for Supporting HVAC Type Design Knowledge in Web-based Collaborative Design Process", Journal of Architectural Institute of Korea, Vol. 23 No. 2, pp. 217-225.

Xue, X., Shen, Q., Fan, H., Li, H. and Fan, S. (2012) "IT supported collaborative work in A/E/C projects: A ten-year review", Journal of Automation in Construction, Vol. 21, pp. 1-9.

Yang, Z., Lu, J. and Elgamal, A. (2004) "A web-based platform for computer simulation of seismic ground response", Journal of Advances in Engineering Software, Vol. 35 No. 5, pp. 249-259.