 CMES, vol.68, no.1, pp.25-53, 2010

Creative Design of Multi-Layer Web Frame Structure Using Modified AHP and Modified TRIZ Clustering Method

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Abstract: This study considers loadings on the multi-layer web frame structure and uses a novel method of the modified analytical hierarchy process (AHP) combined with modified theory of inventive problem solving (TRIZ) clustering to perform the creative structure design. The engineering knowledge of multi-layer web frame structure comprises such issues as vibration, yielding and buckling strength. Using the modified AHP, this study firstly applies the ratios of occurrence numbers of related keywords on different hierarchies to analyze the techniques and functions of multi-layer web frame structure, and finds out the priority order of feasible design decisions. Furthermore, this study also proposes the application of modified TRIZ clustering method to find out the priority order for TRIZ inventive principles and un-worsened parameter groups by a developed program, and then undergoes the innovation and improvement of local design so as to acquire a better design. In the process of knowledge analysis, this study carries out multi-hierarchy analysis and investigation of the relationship between loads and pillar. Thereafter, this study step by step uses finite element method (FEM) to perform stress verification, and then it completes the innovative design of multi-layer web frame structure.

Keywords: Multi-layer web frame structure, AHP, TRIZ clustering, FEM, innovative design

1 Introduction

Generally, it is very difficult for traditional trial-and-error method to rapidly acquire effective decisions, so it increases the time required for design. With the evolution of computer processing speed, structural design and analysis is made to integrate with expert knowledge, making it become more practical and feasible.

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Currently as we know, knowledge-based engineering application is gradually prevailing. For example, Chapman and Pinfold (1999) discussed about the application of computer-aided design (CAD) and knowledge engineering, and established by principles an environment for framework classification and model establishment. By using rules, they established an environment for framework classification and modeling. Jones and Harrison (2006) adopted knowledge engineering method, CommonKADS, to construct an organizational, working, agent and knowledge model. They established alarm surveillance and provided suggested information to reduce the operation load. Miyamoto *et al.* developed K-KARDS system and established knowledgebase of rules to deal with the structural design problem of vessel to shorten the working time. Despite the availability of applications that correlate with computer-aided engineering (CAE) to assist in design (Zhang *et al.* 1996; Li and Zhang, 1998; Bravo-Aranda *et al.*, 1999), they are seldom combined with agent to perform knowledge coding and design applications. In terms of knowledge agent, Wang *et al.* (2002) established institution agents, including the function, energy, state and actual relationship among different agents, and described some frameworks of manufacturing system. While adopting their previously developed method in decision making based on simulated computed policy functions in a multi-agent system, Damba and Watanabe (2008) developed a multi-agent system design for efficient control with hierarchical representation that is closely related to agent modeling features. While performing fuzzy clustering analysis, Wang developed a fuzzy clustering method based on a genetic algorithm. The analytical hierarchy process (AHP) is an evaluation method that can use complex data to establish a clear, layered hierarchical system. Decision-making (Saaty, 2004; Feng *et al.*, 2009) are also common in optimization and decision-making literature. Most of them studied on a specific topic. The combination of applying AHP with innovation design method is seldom seen.

On the aspect of structure analysis, there are many researchers study by using finite element method. For instance, Raju *et al.* (2007) adopted a detailed finite element analysis of the right rear lug of the American Airlines Flight 587- Airbus A300-600R to perform the National Transportation Safety Board's failure investigation of the accident that occurred on November 12, 2001. Alaimo *et al.* (2008) proposed global and local model using two kind of numerical methods. The accuracy and the effectiveness of the model had been demonstrated analyzing classical stress concentration problems for the analysis of advanced aerospace structures. Lin *et al.* (2009) used an integrated finite element-based computational framework to develop for predicting service life of RC structures exposed to chloride environment. As for the optimization aspects, sometimes, topology optimization is regarded as a better method for solving the structural optimal design problem and for producing good overall structure (Tanskanen, 2002). Hughes adopted modeling technology to investigate the principle of structural design, which includes the theoretical and practice application.

TRIZ is a method for solving inventive problems, which was developed by a Soviet scholar, Altshuller in 1946 after he had analyzed thousands of high-level patent descriptions (Altshuller, 2000). Altshuller thought that almost all the invention problems had at least one contradicting phenomenon. It implied that if it attempts to improve a certain feature of a system, then another feature may be worsened. Furthermore, these inventions were always determined by the solving way of contradicting problem. According to the traditional TRIZ method, the contradiction matrix is composed of 40 summarized invention principles and 39 engineering parameters, which can be extracted all from the knowledge foundation in the past invention patent documents. In other words, according to these suggested 40 invention principles and the contradiction and conflict matrix, appropriate problem solving direction can be acquired in the problem solving process. On the aspect of TRIZ theory and application, Chang and Chen (2004) used a series of TRIZ methods to perform green innovative design. Chang and Chen (2004) combined TRIZ with eco-tools to construct contradiction, and solved the eco-design tool problem of CAD software. Wang *et al.* (2005) combined quality function deployment (QFD) with TRIZ to create an effective design method of innovative product. Lin and Chen (2008) used multi-step modified TRIZ to study and analyze the innovation procedure for the calculation of polishing frequency of compensated chemical mechanical planarization (CMP).

The above-mentioned studies mainly stressed the aspect of individual specific topic, like classification, strength analysis, TRIZ theory and application, but they seldom touched upon the combination of AHP and TRIZ to make design decision and innovation rule. Therefore, this study proposes establishing an engineering knowledge prototype framework of multi-layer web frame structure as the foundation. According to the defined knowledge hierarchy for multi-layer web frame structure, the knowledge classification can be obtained. Through the appearance frequency of knowledge keywords at different knowledge hierarchies, and using the modified AHP, the commonly used ratios of occurrence numbers of technique terms and function terms can be acquired. It can provide a reference of the priority order of innovative R&D decisions. This study further examines the new design directions step by step using the modified TRIZ clustering method to find the priority order of innovation principles. Then, finite element method could be used to verify the new innovation structural design for multi-layer web frame structure. In this study, by using the above proposed novel systematic design procedure, it could short the design decision time and find innovation structure quickly.

2 Decision evaluation and innovative design methods of multi-layer web frame structural design

Taking multi-layer web frame structure as the basis, the systematized design decision evaluation and innovative design method proposed by this study firstly collects dozens of patent and engineering technique knowledge documents with relation to multi-layer structure, and then analyzes the techniques and functions. Focusing on the related parameters of structural design, technique and function matrix is established. Thereafter, according to classification of hierarchies, analysis of engineering knowledge framework is conducted. Together with the use of technique and function knowledge of multi-layer web frame structure, further modification is made, intending to achieve a technique to be used by a certain function. The correlativity of hierarchical knowledge framework is adopted to establish the relational engineering knowledgebase of multi-layer web frame. With the collected techniques or patent documents, the experience and knowledge of experts can be acquired. According to the ratios of occurrence numbers of the techniques and function of multi-layer web frame structure, and using modified AHP, the relative weighing ratios of techniques and functions are calculated respectively. Based on the two ratios, the eigenvectors and maximum eigenvalue are calculated, and the relative importance evaluation of feasible techniques is conducted. The priority order of techniques is taken as a basis for evaluation of systematized design decisions and design improvement.

This study also proposes the application of modified TRIZ clustering principle. With the use of feature groups and innovation principles, and through different important parameters, analysis and comparison are made. The 39 feature parameters and 40 invention principles of TRIZ contradiction and conflict matrix are rearranged as different classified groups according to their physical meanings. This study probes into the improving parameters and non-worsening parameters of multi-layer structural design. After cross referencing and selection of prioritized decisions, improvement and innovation directions can be found. In which, special attention should be paid to the homologous relationship between features and inventive principles. Thereafter, the spirit of TRIZ contradiction and conflict matrix is imitated (Altshuller, 1997). In the constructed modified TRIZ clustering method, the concept of groups is used to improve the original TRIZ contradiction and conflict matrix. Then, the use of feature parameters or principles should be considered when conducting design.

This study has a main advantage that through systematized design considerations, design engineers are able to acquire suitable information and design improvement guidelines readily, and propose a design plan that fulfills reinforcement and lightweight requirements in order to shorten the time of design and raise the design efficiency of multi-layer web frame structure. The new concept and method developed in this study, which make design considerations through the analysis of engineering knowledge framework as well as the combination of modified AHP and modified TRIZ clustering principle, are unprecedented in the application of knowledge engineering. The related definitions, formulas, principles and corresponding implementation methods are explained as following sections.

3 Knowledge framework of multi-layer web frame structure

Knowledge framework analysis is a systematized survey and analysis conducted through a planned procedure and examination, as well as the use of hierarchical analysis, so as to find out the correlativity in between. In order to let parameters analyze and apply knowledge framework readily, related knowledge of multi-layer web frame structure is classified. Using hierarchical framework classification, systematized accumulation and analysis are carried out. Based on the analysis results, knowledge application framework is established step by step. The knowledge framework of multi-layer structure includes types of structure, sub-system of structure, techniques and functions, boundary conditions, applied engineering theories and methods, and related constraints.

A web frame structure consists of a transverse beam and a side frame, both forming the foundation of a multi-layered structure. Regardless of the number of factories or the sailing vessels, these are extended applications of multi-layer web frame structure. The geometric shape of a multi-layer web frame structure includes width, height, opening and thickness. By accumulating pertinent reference data and design cases, this study divides the subsystem of web frame structure components into a subsystem with a toggle plate, subsystem without a toggle plate, lapped subsystem and pillar subsystem according to the difference in function and design patterns.

Sub-system with a toggle plate is mainly composed of a transverse beam, a side frame and a bracket plate, whereas sub-system without a toggle plate is composed of a transverse beam, a side frame and a bracket plate. Moreover, pillar subsystem mainly supports the transverse beam structure with excessively great span, making the overall structural arrangement tend to be rationalized. Using sub-system with toggle plate to combine with pillar subsystem is most commonly considered when improving local stress concentration. When meeting local strength requirement, reinforcement plate is also adopted. In the sub-system with toggle plate, different patterns of bracket plates can be designed according to different function requirements, extent of difficulty of construction work and cost consideration.

The main functions of multi-layer web frame structure include supportive structure, light-weight, conformance to strength requirement and buckling requirement. In order to achieve the selected functions, the techniques needed to be considered including local reinforcement, material change, arrangement change and geometry change.

Focusing on multi-layer web frame structure, this study analyzes and evaluates the searched related engineering knowledge documents and patent documents, and then proposes some technique and function terms, which are explained as follows:

(1) Local reinforcement: Local reinforcements are generally used to reinforce neighboring structures and thereby alleviate stress concentration.

(2) Arrangement change: The design of arrangement must be altered to meet special requirement, arrangement change has to be carried out. The techniques for changing arrangement can be dealt with two ways. One is changing the arrangement of loading pattern, and this directly affects the load distributions. The other one is changing the structure configuration. This can reduce the loading of the structure, reduce deformation or increase strength, making a design increasingly rationalized.

(3) Material change: Use different structural materials, and refer to related functional and strength requirements to match with the design of members to improve the overall weight of the structure and fulfill the strength requirement.

(4) Geometry change: Change the overall geometry of structure, such as its width and depth, so as to change the value of load distribution.

(5) Supportive structure: An overall structure must be supported by vertical and horizontal members, which should be connected to provide strong and powerful supportive functions and meet design requirements.

(6) Light-weight: The directions of light-weight include the minimization of components, changes to structure dimensions and material change. The designs are matched with the object functions, limitations, loadings, boundary conditions to achieve a light-weight structure.

(7) Yielding requirement: When designing a structure based on the safety consideration, the properties of internal members must first fulfill the yielding strength requirement.

(8) Buckling requirement: If the load of structure exceeds critical load, buckling will be occurred to the structure. After external force is removed, the original shape of structure cannot be resumed.

As seen from the analyzed classification results of multi-layer web frame structure in Figure 1, the engineering knowledge framework includes relational engineering knowledge, such as structure type, structure sub-system, technical function, boundary condition, constraint and application of engineering principles methods. According to the analytical results of framework, together with the hierarchy knowledge and the knowledge framework, the engineering knowledgebase interface of Figure 2 can be established. The technique and function matrix relating to multi-layer web frame structure is shown in Table 1. Based on the parameters of Table 1, the knowledgebase of techniques and functions is established. The systematic procedure of applying agents interface program to analyze multi-layer web frame structure is shown in Figure 3.

Table 1: Technique and function matrix of multi-layer web frame structure

Function / Technique	supportive structure	light-weight	yielding requirement	buckling requirement
local reinforcement	seam, connecting plate, bracket, welding, rivet joint, ..	seam, connecting plate, bracket, welding, stiffener, ..	seam, connecting plate, bracket, welding, concentration, ..	bracket, welding, scantling, thickness buckling ratio, ..
arrangement change	transverse, longitudinal, spacing, scantling, girder, stiffeners, ..	transverse, longitudinal, spacing, scantling, geometry, loading pattern, span, ..	transverse, longitudinal, spacing, scantling, pillar, ..	transverse, longitudinal, pillar spacing, clear height, pillar, slender ratio, buckling ratio, feature length, ..
material change	density, high-tensile steel, resist loading, support member, ..	density, aluminum alloys, glass fiber, high-tensile steel, minimum weight, material property, ..	density, high-tensile steel, young's modulus, deflection, stress, ..	material, buckling ratio, ultimate strength, ..
geometry change	geometry, shape, clear height, span, ..	geometry, shape, ..	geometry, shape, clear height, span ..	geometry, shape, pillar, clear height, buckling ratio, feature length, ..

When designing a multi-layer web frame structure, the shape and design has to be considered based on actual spatial need and load conditions so as to meet the needs of work. When the span is designed with longer spacing, it may have problems of

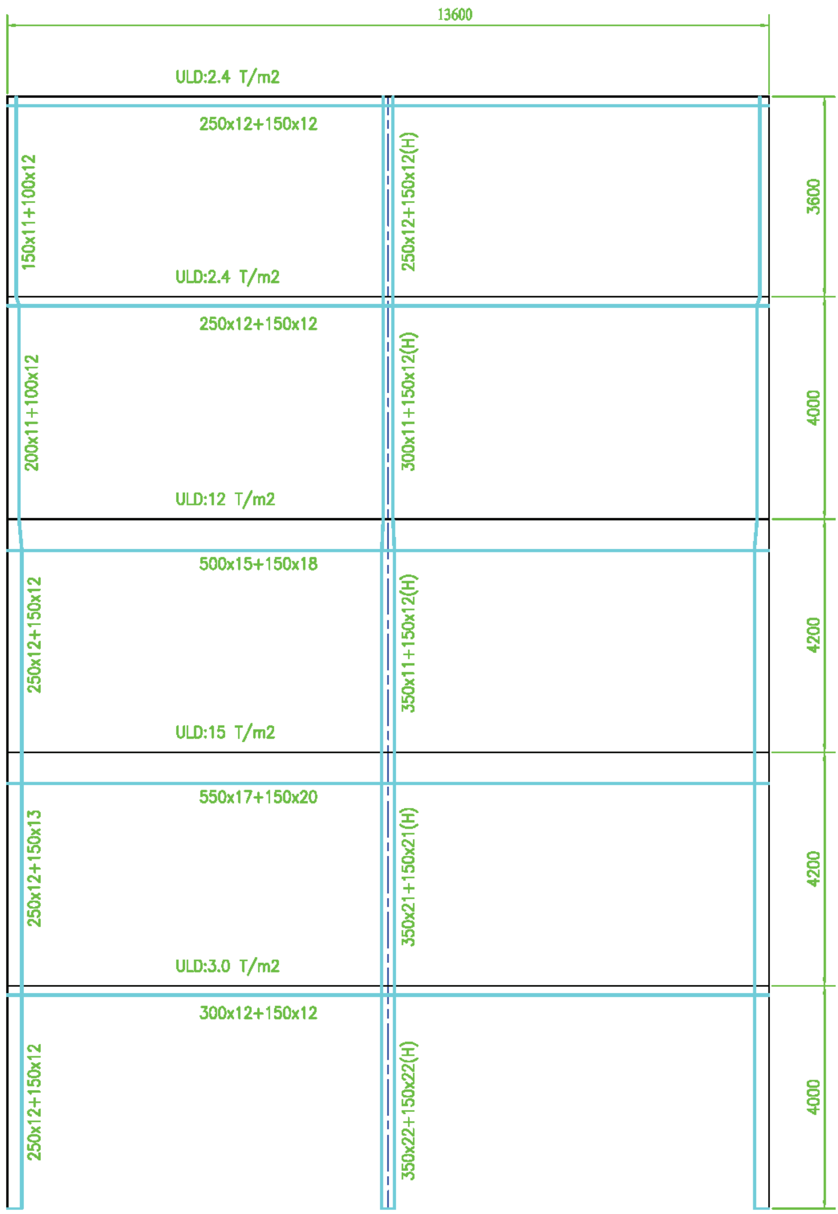

Figure 1: Indicated design drawing of multi-layer web frame structure

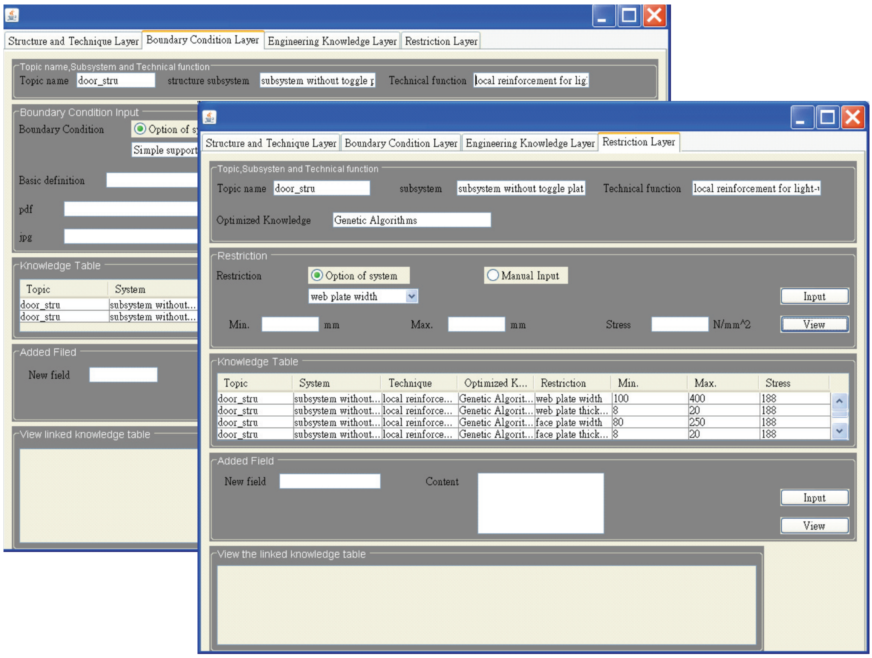

Figure 2: Part of relational engineering knowledgebase program interface of multi-layer web frame structure

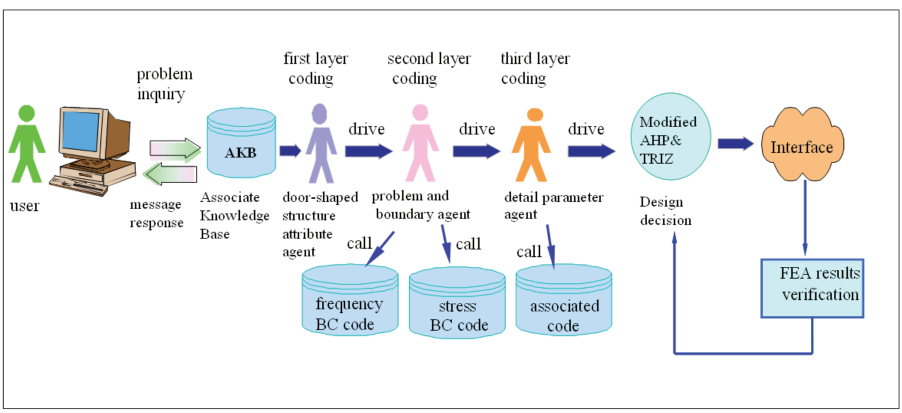

Figure 3: Systematized structural diagram of application of agents to multi-layer web frame structure design decision and results verification

buckling, vibration or stress concentration. In order to solve the induced problems, this study proposes related methods, including analysis of engineering knowledge framework, together with the adoption of the decision evaluation of the priority order of techniques and innovative design methods so as to acquire rationalized design rapidly, make optimal design decisions, and integrate related calculation and application.

Concerning the engineering principle method of a web frame structure, designing and analyzing the transverse beam vibration of a multi-layer web frame structure require considering mass, stiffness, displacement and exciting force. The governing equation is shown as follows:

$$[m]\left\{\ddot{D}\right\}+c\{\dot{D}\}+[K]\{D\}=F \tag{1}$$

When damping effect and exciting force are not considered, equation (1) is simplified as follow:

$$[m]\left\{\ddot{D}\right\}+[K]\{D\}=0 \tag{2}$$

Where $[m]$, $[K]$ and $\{D\}$ are mass, stiffness and displacement matrix, respectively. Equation (2) is an eigenvalue problem. Its eigenvalue is just the natural frequency of structure. Suppose that the component is a steel-made simple support beam, then the natural frequencyf_n can be calculated by the following equation.

$$f_n=5120\ c\sqrt{\frac{I}{A}}.\frac{1}{l^2} \tag{3}$$

Where c is the boundary condition parameter, I is the moment of inertia (m^4), A is the section area (m^2), and l is the length of beam (m). The modified length l' of bracket can be set as two-thirds of the bracket length when there were bracket plates at both sides of the structure, and the length of beam may be revised to $l-2l'$. Besides, to a simple support beam with uniform load w, its bending moment distribution is:

$$M=-\frac{wlx}{2}(1-\frac{x}{l}) \tag{4}$$

As for the simple support beam with central-concentrated load W, when , the bending moment M, can be expressed as follows:

$$M=-\frac{Wx}{2} \tag{5}$$

By using bending moment M and section modulus Z, the corresponding stress σ can be acquired, that is:

$$\sigma = \frac{M}{Z} \tag{6}$$

The calculation of pillar's buckling can be expressed as equation (7):

$$P_{cr} = \pi^2 EI/L_e^2 \tag{7}$$

where P_{cr} denotes critical load, and L_e denotes feature length.

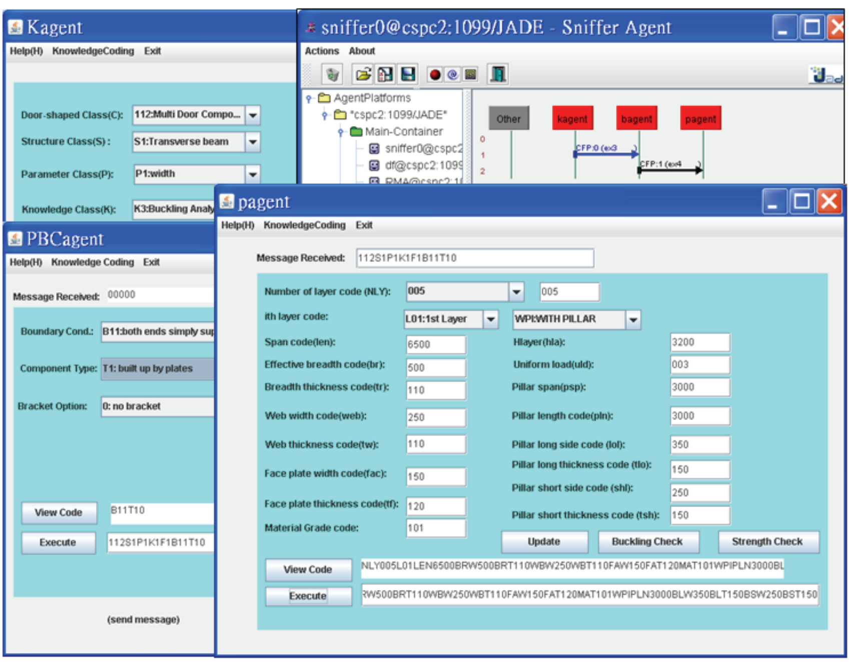

Figure 4: Information transmission between various agents and codes of multi-layer web frame structure

The information transmission among different agents in this application system is shown in Figure 4. The program interface of buckling agent established by combination with MySQL database is shown in Figure 5. Through this program, the buckling strength of different layer structures can be evaluated.

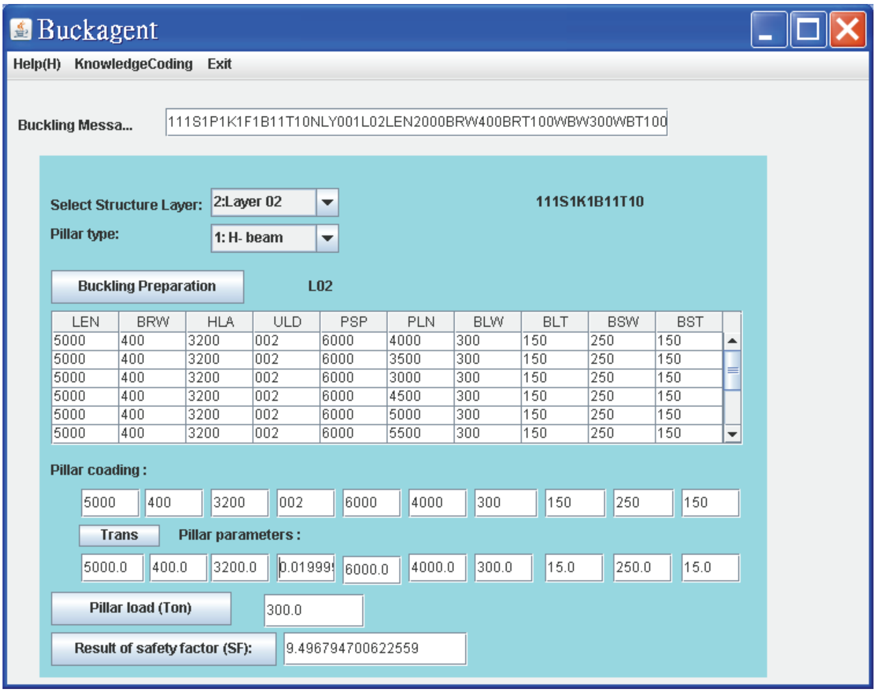

Figure 5: Program interface of buckling agent

4 Establishment and evaluation of modified AHP

The purposes of the development of AHP are to systematize complicated problems, make hierarchical analysis from different levels, and quantify the subjective judgment. When the context is found, synthetic evaluation is further made to provide suitable information to decision-makers for selection, and decrease decision error. Therefore, from the dozens of proposed technical documents and patent references, this study considers the ratios of occurrence numbers of related technical terms corresponding to different functions; uses modified AHP; takes four techniques, namely local reinforcement, material change, arrangement change and geometry change, as well as four functions, namely supportive structure, light-weight, resonance avoidance, yielding strength requirement and buckling requirement, as an example; and establish pairwise comparison matrix to calculate the maximum eigenvalue. Finally, from the ratios of occurrence numbers of these techniques and functions, and according to the weighting relationship of appearance frequency, the evaluation scale is adjusted and modified, and the hierarchical importance of different hierarchical essential factors can be calculated. The main procedures of modified AHP applied by this study are summed as follows:

(1) Establishment of pairwise comparison matrix

First, programs are used to search documents of different patents and techniques. Under a certain function, the appearance frequency of different technical terms is found, and its ratio is calculated by equation (8). This study makes some suppositions: supportive function (k=1), light-weight function (k=2), yielding requirement function (k=3) and buckling requirement function (k=4); and local reinforcement (i=1), arrangement change (i=2), material change (i=3) and geometry change (i =4). Then, the appearance frequency ratio e_{ik} is as follows:

$$e_{ik} = f_{ik} / \sum_{i=1}^{n} f_{ik} \tag{8}$$

where f_{ik} denotes the number of times the technical term occurs, and n denotes the number of techniques.

(2) Consistence check

The purpose of calculating maximum eigenvalue and eigenvector is to inspect whether pairwise comparison matrix [A] meets consistence requirement. First, pairwise comparison matrix [A] is multiplied by the acquired eigenvector $[W]_{nx1}|_k$ to generate a new vector $[W']_{nx1}|_k$. Then, the maximum eigenvalue,$\lambda_{\max}|_k$, is derived by equation (9).

$$\lambda_{\max}|_k = \frac{1}{n}(w'_{1k}/w_{1k} + w'_{2k}/w_{2k} + \ldots + w'_{nk}/w_{nk})|_k \tag{9}$$

(3) Relative importance evaluation

As mentioned above, focusing on the feature values (w_{11}, w_{21}, $w_{31,}w_{41}$) of supportive structure function towards four techniques, the feature values (w_{12}, w_{22}, $w_{32,}w_{42}$) of light-weight function towards four techniques, the feature values (w_{13}, w_{23}, $w_{33,}w_{43}$) of strength requirement function towards four techniques, and the feature values (w_{14}, w_{24}, $w_{34,}w_{44}$) of buckling requirement function towards four techniques, a feature value matrix is formed as equation (10).

$$[\mathrm{W_t}]_{nxn} = \begin{bmatrix} w_{11} & w_{12} & \ldots. & w_{1n} \\ w_{21} & w_{22} & \ldots. & w_{2n} \\ \ldots. & \ldots. & \ldots. & \ldots. \\ w_{n1} & w_{n2} & \ldots. & w_{nn} \end{bmatrix} \tag{10}$$

The relative importance of structure design technique can be expressed by $[\mathrm{X}]_{nx1}$ matrix of equation (11).

$$[X]_{nx1} = [W_t]_{nxn}[W_f]_{nx1} \tag{11}$$

This paper takes the appearance frequency of four functions, namely supportive structure, lightweight, strength requirement and buckling requirement as examples, and then conducts importance evaluation of four feasible techniques. The importance evaluation is taken as a basis for innovative design of multi-layer web frame structure. As for the modified AHP, the relative importance evaluation results of the combination of four functions and four techniques of the multi-layer web frame structure are shown in Figure 6.

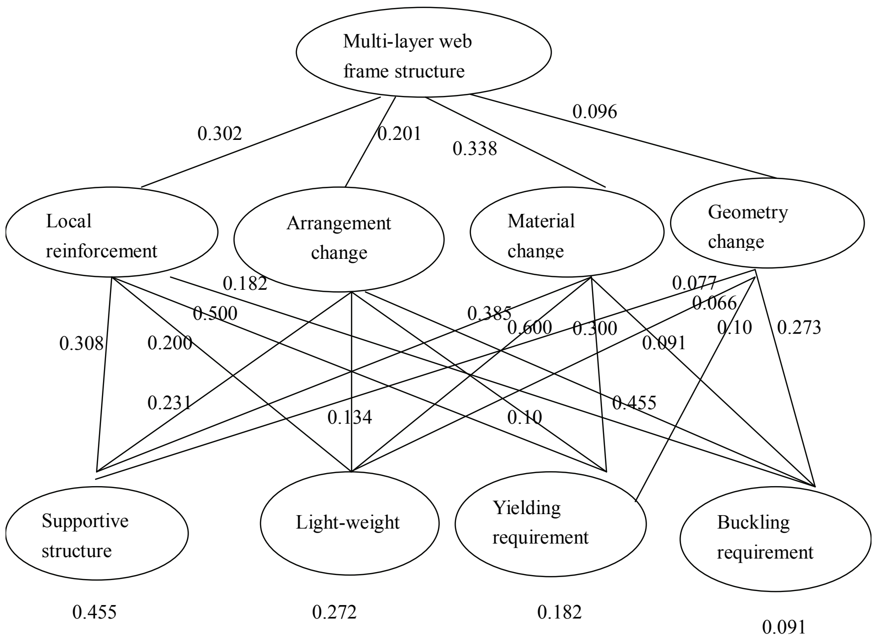

Figure 6: Evaluation of relative importance of four techniques and four functions

5 Combining modified AHP with modified TRIZ clustering method to conduct innovative design

Altshuller asserted that contradiction problems should be solved by engaging in innovative activities. However, only one improving feature can be selected each time from the TRIZ contradiction matrix to improve the invention, knowledge, vision and analog for reference must be obtained to determine the improvement. TRIZ is the theory of solving inventor's problems. The development of this technique opens up the application of innovative engineering. When an inventor has a design problem and intends to improve an engineering property, another engineering property is commonly worsened. The analytic summary of Altshuller reveals 39 system features that are frequently traded off against each other. The inventive rules of their corresponding solutions are rearranged as a matrix, producing the most well-known contradiction matrix in the TRIZ method (Altshuller, 1997).

Generally, on the aspect of inventive rule or un-worsened parameters, traditional TRIZ is not easy to decide for designer. Furthermore, it will spend quite a lot of time to examine the related techniques. So the modified TRIZ is used in this study, and the modified TRIZ uses the concept of modified clustering method, it clusters improved parameter, inventive rule and un-worsened parameter, then it can quickly acquire the priority of inventive rule and un-worsened parameter.

When the number of times of each inventive principle or un-worsened parameter appears in each group of inventive method or un-worsened parameter, the ratio of number of times is calculated using equation (12).

$$e_i = f_i / \sum_{i=1}^{n} f_i \qquad (12)$$

where, f_i is the number time an inventive principle or un-worsened parameter occurs, and n is the number of each clustering. Generally, by human thinking, it is thought that the higher ratio of number of times is used as the higher priority for deciding the group inventive method or the group un-worsened parameter in the modified TRIZ method.

Finally, it goes back to traditional TRIZ for further check and obtains the final inventive rule (Altshuller, 1997). This method can be quickly acquired the priority order of inventive rule. This study proposes a novel method by using the modified AHP to conduct evaluation of feasible techniques, and then combines it with modified TRIZ clustering method using a developed program to rapidly conduct innovative multi-layer web frame structure design.

Table 2 shows a traditional TRIZ contradiction matrix, which is composed of a 39×39 feature matrix and 40 inventive principles. On the vertical axis is presented with 39 improving features, whereas the horizontal axis is presented with 39 worsening features. This study suggests applying modified TRIZ clustering method to rearrange the 39 feature parameters and 40 invention principles in the TRIZ contradiction matrix to be classified groups according to their similar physical meanings. During such rearrangement, attention has to be paid to the corresponding relationship between features and invention principles. Thereafter, the spirit of TRIZ contradiction and conflict matrix is imitated. In the constructed TRIZ clustering procedure, clustering concept is used to improve the original TRIZ contradiction and

Table 2: Simplified table of TRIZ contradiction matrix (Altshuller, 1997)

Worsening Feature / Improving Feature	1 Weight of moving object	2 Weight of stationary object	3 Length of moving object	…	39 Productivity
1 Weight of moving object	+	-	15,8,29,34	…	35,3,24,37
2 Weight of stationary object	-	+	-	…	1,28,15,35
3 Length of moving object	8,15,29,34	-	+	…	14,4,28,29
……………………….	…	…	…	+	…
39 Productivity	35,26,24,37	28,27,15,13	18,4,28,38	..	+

conflict matrix. Then, this study considers the adoption of which feature parameter or principle using the priority order of inventive rules from a developed program to quickly acquire the design parameters. The modified clustering method of 39 features is to categorize the related elements with similar physical meanings to be 10 groups, including mobile objects, non-mobile objects…and physical nature. The clustering principle of invention rules is to categorize the related elements with similar physical meanings to be 13 groups, including object division and extraction group, advanced handling…and system combination (Lin and Chen, 2008).

Taking multi-layer web frame structure as the foundations, and focusing on the related parameters planed for structural design, this study establishes technique and function matrix. Based on feature groups and innovation principles, analysis and comparison are made through different important parameters. This study proposes a novel method for combining the priorities of design decisions using a modified AHP and a modified TRIZ clustering method for multi-layer web frame structure. By using the combining method, we can quickly investigate the improving parameters and non-worsening parameters in the design of multi-layer support structure. The integrated design process of multi-consideration by modified AHP and modified TRIZ clustering method is shown in Figure 7. Based on the clustering priority of subject technique, one can rapidly judge a better way to revise the design. It has the advantage to quickly judge a good technique for design. Furthermore, the innovation design can be found more rapid and effective than that of the traditional method. Thus, obviously shortening the working time compared with the trail-and-error method. Therefore, based on the design process from Figure 7, the iterative revised design is examined by systematic consideration combined with modified

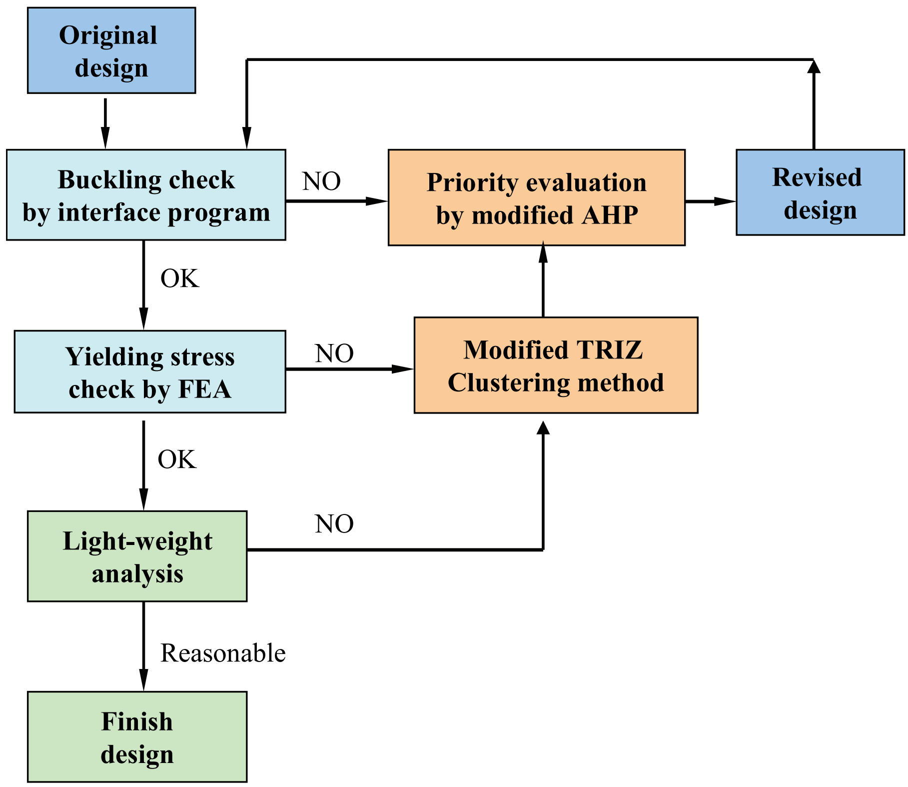

Figure 7: Design process of multi-consideration by modified AHP and TRIZ clustering method

TRIZ clustering method step by step using the priority order of inventive principles from a developed program to rapidly and effectively get an innovation design direction. After cross referencing and selection of prioritized decisions, improvement and innovation design directions can be well found, and then a new multi-layer web frame structure can be designed.

6 Case study and analysis verification of innovative design of light-weighted multi-layer web frame structure

This study combines modified AHP with modified TRIZ clustering method to conduct multi-layer structure light-weight analysis. After that, this study step by step uses finite element method (FEM) to analyze the stress of each structure component, which is taken as the basis for assessing whether a design is good or bad. In the aspect of engineering, the problem solving covers two parts, analysis process and optimization. Generally speaking, in the analysis process, some unknown parameters are supposed first, and FEM is then used to solve the problem, obtaining a group of numerical solutions. Besides, in times of traditional calculation, empirical formula can also be used. Through boundary conditions and different physical properties, such as section area, effective length and moment of inertia, similarity analysis is conducted. Furthermore, the stress distribution of structure is calculated. After rearrangement, a comparison diagram of reasonable section areas of structure under different loading conditions can be acquired, as shown in Figure 8.

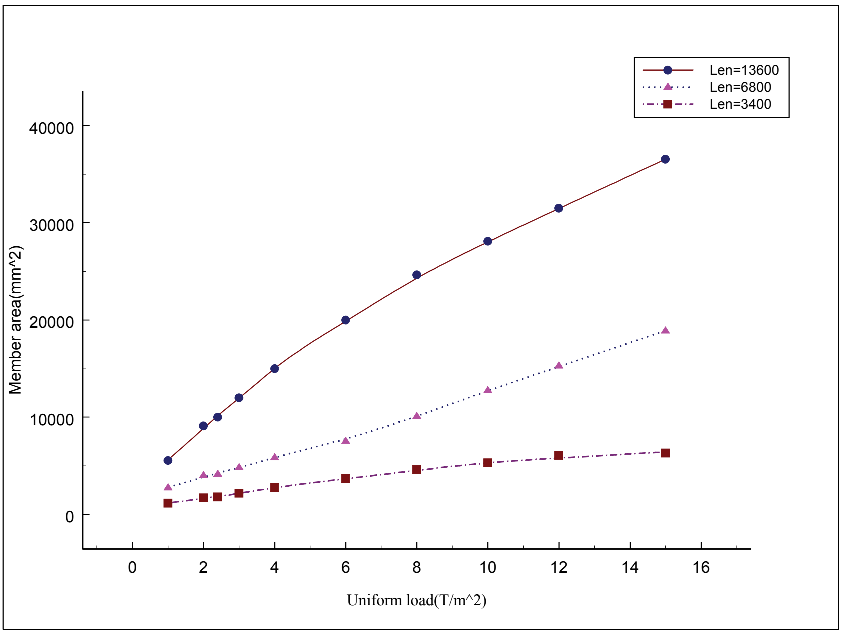

Figure 8: Comparison diagrams of section areas under different loading conditions

6.1 *Priority evaluation of buckling using Modified AHP*

Taking a 5-layer support structure as a case study, this study makes analysis of buckling, yielding stress and light-weight. It is supposed that the width of the original structure is 13.6m, and the heights of the 1^{st} to 5^{th} layers are 4 m, 4.2m, 4.2m, 4m and 3.6m, respectively. The structure of each layer is applied with different uniform loads. Using the method mentioned in Section 4, pairwise comparison matrix is established. The eigenvectors and maximum eigenvalue are calculated, and the relative importance evaluation of different techniques and functions is made. As seen from the importance evaluation results of AHP matrix, the most commonly used techniques of multi-layer web frame structure design are material change, local reinforcement, arrangement change and geometry change (Figure 6). As for the techniques relating to buckling requirement, the priority order is arrangement change, followed by geometry change and local reinforcement. For the techniques relating to yielding requirement, the priority order is local reinforcement and material change. In addition, the techniques relating to lightweight function, the priority order is material change, followed by local reinforcement and arrangement change. If material change is not considered first, then in general, arrangement change and local reinforcement are still the main thinking directions.

Suppose that a 5- layer structure with its transverse beam being 13.6m long is taken for example. If the uniform load of the 1^{st} layer is $3.0T/m^2$, the uniform load of the 2^{nd} layer is $15T/m^2$, the uniform load of the 3^{rd} layer is $12T/m^2$, and the uniform load of the 4^{th} and 5^{th} layers is $2.4T/m^2$, then the structure of each hierarchy has to meet buckling requirement (let the considered minimum buckling safety factor be 5.0) and yielding strength requirement before making lightweight design.

Taking the 2^{nd} layer structure of the multi-layer web frame structure for example,

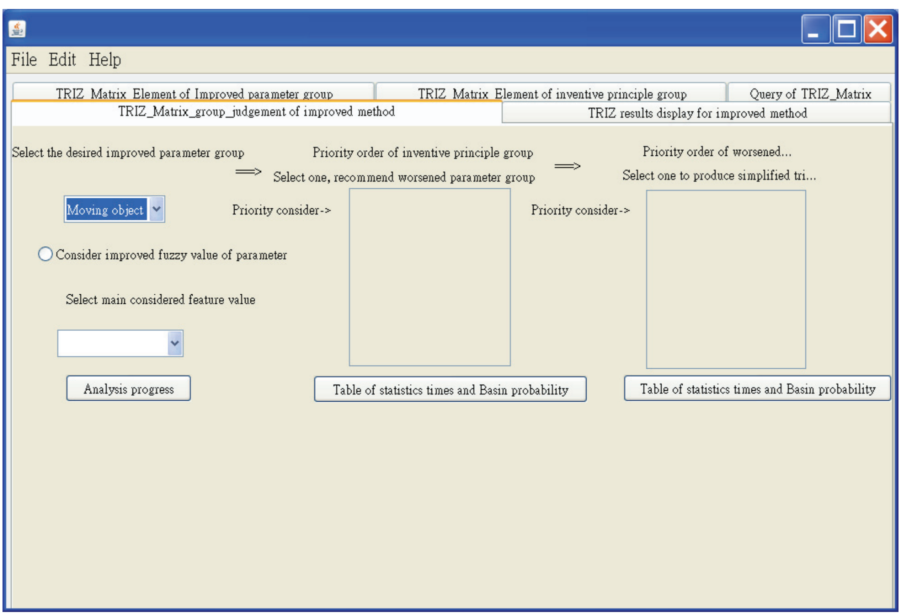

Figure 9: Invention principles with prioritized consideration of physical property

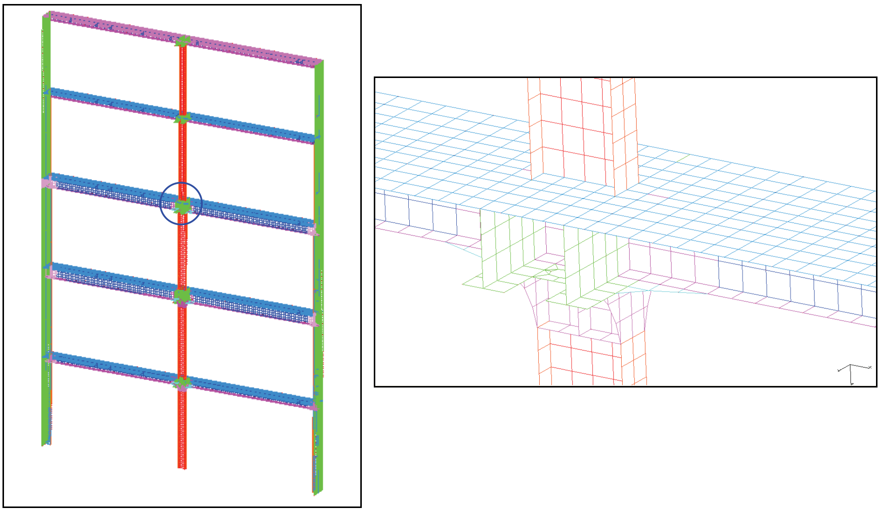

Figure 10: Schematic diagram of innovative design of multi-layer web frame structure at pillar

its uniform load is 15T/m^2. When additional pillar is not added, the length of the transverse beam is 13.6m. After calculation, the accumulated support load is as heavy as 173.0 tons. First of all, its buckling ratio is inspected according to equation (7). If the side frame dimension is 150x11+100x12, its buckling ratio is 2.4, which is obviously smaller than the safety tolerance value of 5.0. According to the modified AHP evaluation results, arrangement change and geometry change are most effective for design improvement of buckling problem. Therefore, the change of geometric shape can be firstly considered. The side frame dimension is changed to be 250x12+150x12, and then its buckling ratio is 8.9, which meets the buckling requirement. Thereafter, multi-layer structured finite element analysis (FEA) model (Figure 10) is established to further inspect the yielding strength. The corresponding FEA results are shown in Figure 11. Since the span of the transverse beam is greater, the stress value is rather high. As shown from the analysis results, when the total length of the transverse beam without pillar is 13.6m, its maximum von Mises stress reaches 962 N/mm^2, which is obviously excessively high. If material change is not considered, the results acquired from modified AHP can be used, adopting the 2nd prioritized order of local reinforcement or the 3rd prioritized order of arrangement change to reduce the high stress.

6.2 Innovation design combining modified AHP with modified TRIZ clustering method

Since the span of the transverse beam is rather great, if purely adopting local reinforcement for strengthening, the effect is limited. Even if bracket plate is used to perform local reinforcement, the stress is still as high as 916 N/mm^2 (Figure 12). Therefore, it is most ideal for local reinforcement to be matched with the 3rd prioritized arrangement change. First of all, the design of different pillars is considered, and section design is conducted to meet the buckling requirement, and lightweight is taken as the goal. In general, when buckling design is carried out, the applied force, pressure, slenderness ratio, strength and balance object have to be considered. As for lightweight design, it has to consider material, object division, local structural change and mechanical system (arrangement) change. The main functions of pillar include supportive structure, support load, load dispersion and depth improvement of transverse beam.

Table 3: List of the use of groups to improve buckling, but without worsening of pressure

group of worsened parameter / group of innovation parameter / group of improved parameter		physical properties	9 velocity 10 force 11 tension/compress 12 shape 13 object stability 14 strength
Physical properties	9 velocity 10 force 11 tension/compress 12 shape 13 object stability 14 strength	Physical change group	35. change of physical and chemical state 36. change of phase 37. heat expansion

Since it is considered that the change in the arrangement and geometry of AHP meets the buckling and yielding strength requirements, arrangement change is made by additional erection of pillar in the design. In the actual engineering design, when

Table 4: List of buckling improvement, but without worsening of pressure

Not worsened parameters / Innovation principle / improved parameters	11 tension/pressure
13 object stability	35 changes the state, density, concentration, elasticity or temperature of objects

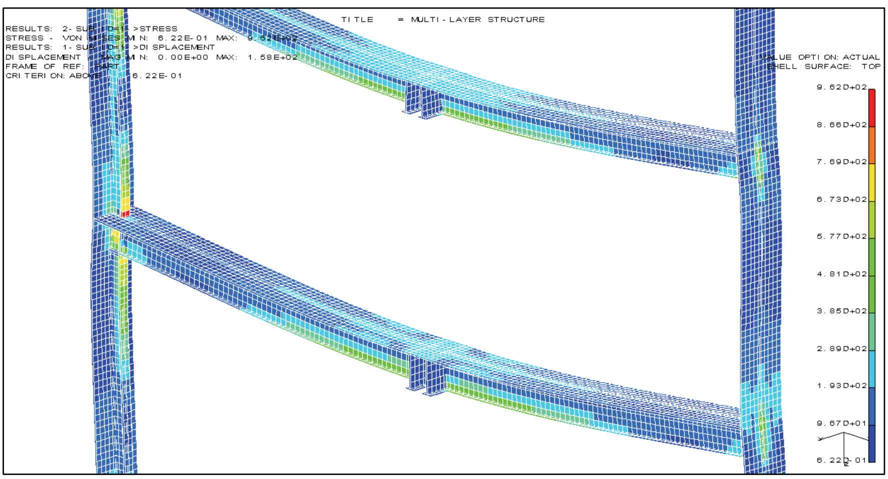

Figure 11: Stress distribution diagram of multi-layer web frame structure under pillar-free condition

it is required to improve the buckling of pillar, the physical nature of improving parameter group is considered. Through implementation of TRIZ group interface program (Figure 9), the 2^{nd} prioritized invention principle group, i.e. physical change, is selected. The invention principles of physical change group include No. 35, change of physical and chemical state, No. 36, phase change, and No. 37, thermal expansion (Table 3). The traditional TRIZ table is further used to conduct analysis.

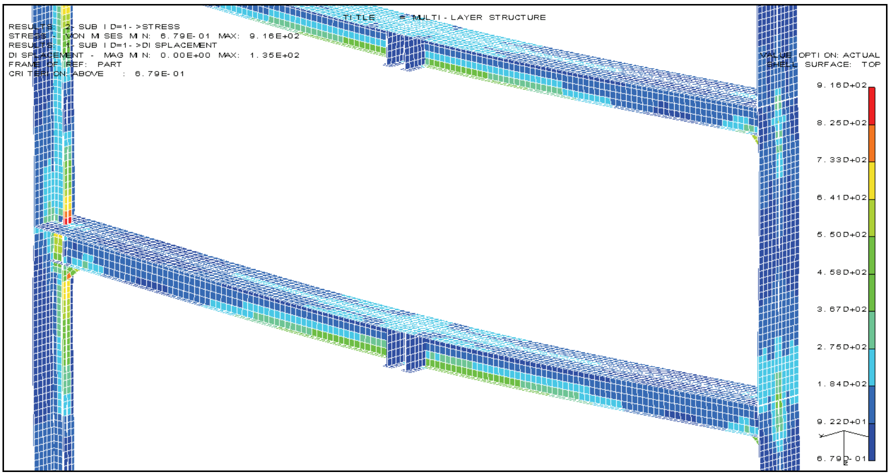

Figure 12: Locally reinforced stress distribution diagram of multi-layer web frame structure under pillar-free condition

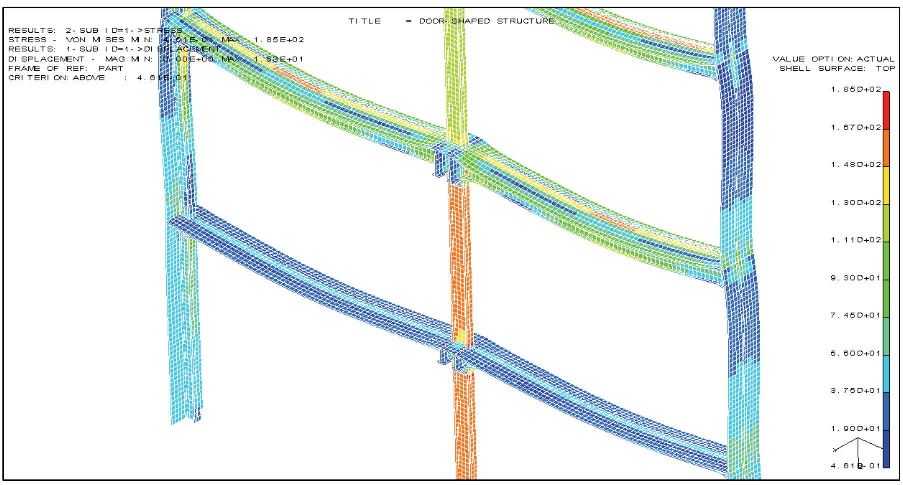

Figure 13: Stress distribution diagram of multi-layer web frame structure under pillar-existing condition

The considered improving function is No. 13, physical stability. It is hoped that stress (i.e. No. 11, pressure or stress) is not worsened, and then the corresponding invention principles are found to be Nos. 2, 35 or 40. In this way, invention prin-

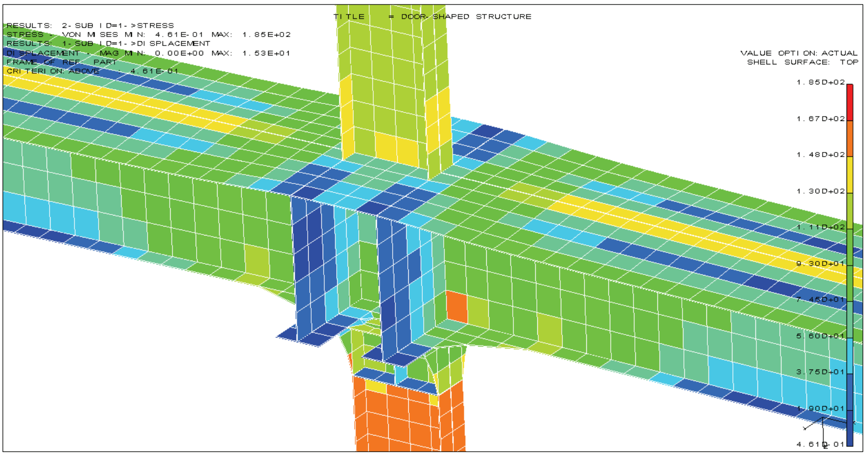

Figure 14: Stress distribution diagram of multi-layer web frame structure at the pillar connection structure on the second layer

ciple No. 35 changes the state, density, concentration, elasticity or temperature of objects (Table 4) to perform change of physical state, and then solve the buckling problem.

After the buckling requirement of pillar is re-inspected, the span of the modified transverse beam is cut half to be 6.55m. The yielding stress is inspected again. In the design additionally erected with pillar and having local reinforcement performed, its maximum stress is 185 N/mm^2 (Figure 13). During this time, the yielding stress has fulfilled the requirement of permissible stress.

Subsequently, this study discusses about quantitative analysis. When material change is not considered, this study refers to AHP and uses the 2nd prioritized local reinforcement technique to undergo light-weight design. At the same time, referring to TRIZ techniques, and let the structure have no total weight increase, then light-weight requirement has to be satisfied. During this time, the improving parameter is feature No. 2, weight of fixed object, and the non-worsening parameter is feature No. 14, strength. The referential invention principles are Nos. 28, 2, 10 and 27. The highly prioritized principle No. 2 (extraction) is taken out for analysis. It reveals that decrease of plate thickness or drilling can meet the requirement. Therefore, the prioritized principle No. 2 (extraction) can be used to decrease the plate thickness in terms of structure material. Nevertheless, the decrease of plate thickness will cause insufficient strength of local regions.

Finally, focusing on strength improvement again and with weight not worsened, analysis is made. During this time, according to TRIZ innovation decisions, the

Table 5: List of strength improvement, but without worsening of weight

Innovation principle (improved parameters / not worsened parameters)	2 weight of fixed object
11 strength	40 synthesized material 1 separation

adoptable invention principle is No. 40 (synthesized material) or No. 1 (separation) (Table 5). When high-tension steel of higher price is not considered, the local separation design is the main direction of design improvement. Hence, this study adopts local weld pass separation to increase dimension and conduct local reinforcement in high stress area, and make replacement by smaller dimension in low stress region, thus respectively completing the detailed design in Table 6. In this design, the typical stress distribution of the second pillar connection structure is inspected, as shown in Figure 14.

According to the above-mentioned modified AHP, modified TRIZ clustering and the innovative decision-making procedure, light-weight is performed, but stress is not worsened. Local reinforcement for synthesizing the multi-layer design considerations are adopted, having completed the innovative design with local separation, as shown in Figure 10. A comparison of related dimensions before and after light-weight of multi-layer web frame structure is shown in Table 6. After this design is compared with the original structure without consideration for local separation design, a weight of around 400 kg can be saved. If the entire design has 50 sections, 20 tons of steel material will be saved.

Focusing on related parameters and according to the above-mentioned design considerations, this study has completed the detailed design of 5-layer web frame structure. This method adopting local separation design of pillar has sufficiently met buckling, yielding and light-weight requirements. The design also employs FEM

Table 6: Comparison of related dimensions before and after light-weight analysis of multi-layer web frame structure

Location	Initial scantlings	Scantlings after improvement	Local design in way of pillar
NO.5 Layer	800x11+250x11+150x12 250x12+150x12	800x11+250x11+150x11 250x11+150x11	no change due to light loads
NO.4 Layer	800x11+250x11.5+150x12 300x12+150x12	800x11+250x11.5+150x12 300x11+150x11	no change due to light loads
NO.3 Layer	800x13+500x16+150x18 350x12+150x12	800x13+500x13+150x16 350x11.5+150x12	800x13+500x16+150x18+BKT 350x11.5+150x12+BKT
NO.2 Layer	800x15+550x17+150x20 350x21+150x21	800x15+550x13.5+150x18 350x18+150x19	800x15+550x17+150x18+BKT 350x21+150x21+BKT
NO.1 Layer	800x12+300x13.5+150x12 350x22+150x22	800x12+300x12+150x12 350x19+150x20	800x12+300x13.5+150x12+BKT 350x22+150x22+BKT

Note: BKT is bracket

to make analysis at each step, thus rapidly showing the advantages and disadvantages of the design for decisions making. Therefore, this knowledge analysis is an integration consideration method combining modified AHP with modified TRIZ clustering method. This model has been proved to be able to be rapidly applied to the analysis and evaluation of design, and to acquire sound and innovative design.

7 Conclusion

This study takes multi-layer web frame structural design for example, and uses knowledge framework to conduct engineering knowledge framework classification. Meanwhile, modified AHP and modified TRIZ clustering method are both used to conduct innovative design of multi-layer web frame structure. Through the ratios of occurrence numbers of the keywords in technical documents, patents and past literature, and according to different function requirements, the weighting value of hierarchical importance required by AHP can be found. Together with modified AHP, and taking four techniques and functions as example, this study analyzes the physical properties, related techniques and functions of structure, and finds out the commonly used sequence ratio of the techniques and functions, effectively providing a reference of the priority order of innovative R&D decisions. This study also proposes the application of modified TRIZ clustering method to conduct innovation and research analysis of engineering design, and find out the priority order of considerations for the TRIZ invention principles groups. Furthermore, modified AHP, modified TRIZ clustering and innovative decision-making method are employed to make improvement and innovation of the multi-layer web frame structural design, so as to acquire a better design. This study further examines the new design directions step by step using the modified TRIZ clustering method to find the priority order of innovation principles. Then, finite element method could be used to verify the new innovation structural design for multi-layer web frame structure. In this study, by using the above proposed novel systematic design procedure, it could short the design decision time and find innovation structure quickly.

Acknowledgement: The authors thank National Science Council, Taiwan, ROC (Grant number NSC-96-2221-E-011-106-MY3) supporting this research.

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