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# PROCESS AND QUALITY IMPROVEMENT USING SIX SIGMA IN CONSTRUCTION INDUSTRY

**Megan Florent Tchidi**[1], **Zhen He**[2], **Yan Bo Li**[3]

[1]*Management Sciences and Engineering, Tianjin University, 92 Weijin Road, Nankai District, Tianjin, China*
[2]*College of Management and Economics Tianjin University, 92 Weijin roads, Nankai District, Tianjin, China*
[3]*School of Civil Engineering, Tianjin University, 92 Weijin road, Nankai District, Tianjin, China*
*E-mails: [1]ftchidi@yahoo.fr (corresponding author); [2]zhhe0321@163.com; [3]liyanbo_tj@sina.com*

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**Abstract.** Construction industry presents an extremely complex combined process, production flow, various structures, high quality requirements and long construction cycle. Large quantities of concrete and time are wasted during building construction due to management procedures, construction processes and reworks. Besides, the final construction quality cannot fully meet customer requirements.

This paper explores practical solutions for construction process and quality improvement by using prefabricated composite structure (PCS) based on Six Sigma method. The D-M-A-I-C model of Six Sigma has been applied to conduct the analysis of the construction process, to discover essential factors to improve and thus to achieve higher customer satisfaction. This research finds out what influences construction process, construction quality and then adopts design and technique correction measures. It improves the construction process, quality resistance to various performances and proposes the best mix proportion. These improvement measures help to overcome and reduce considerably concrete cracking and slippage in building construction. Based on Design for Six Sigma model (Define, Characterize, Optimize and Validate: DCOV) and using the finite element analysis model (ANSYS), this study develops for scientific and economical use in construction industry a composite steel-concrete model.

The proposed approach falls into three phases. Based on measurement and construction process analysis from Six Sigma black belt consultant, construction managers, Engineers, clients, architects, the model helps to find and eliminate critical defects and failure before they occur.

**Keywords:** Six Sigma, construction quality, DFSS, construction industry, process improvement.

## 1. Introduction

In construction industry, customer requirements are constantly increasing. Clients are considered as the most important stakeholder in every construction project (Idoro 2010).

Thus, an important subject in the refurbishment market is how to create and transfer the real value required by the customers, and promote SQ to win customer satisfaction. In the new economic times with fast growing information transfer and emergence of new competitors, many enterprises set business targets on “improving the quality of service and seeking customer satisfaction” (Huang, Hsueh 2010).

The transfer of a maximum of activities from the building site towards a factory becomes inevitable. Many researches (Alinaitwe *et al*. 2006; Blismas *et al*. 2006; Goodier, Gibb 2007; Tam *et al*. 2007a, b; Jaillon, Poon 2009; Pasquire *et al*. 2005; Ko 2010; Polat 2010) have shown the advantages of prefabrication in the construction. Arditi and Mochtar (2000) have showed that the increase in the use of prefabricated components in the building industry would contribute to higher productivity and easier management in quality issues and project control. The use of prefabrication and system formworks were not the only means of reducing construction waste. For Jaillon and Poon (2008), Jaillon *et al.* (2009), the adoption of waste management plans and the trip ticket system were important.

In the past, the quality concept was based on construction drawings and the need to satisfy the required standards. But now, satisfaction of required standards is not enough for quality in the construction industry. Also, it has to satisfy and even please the customer. Idoro (2010) had established that clients consider project quality as the most important factor in the award of contract. In short, quality is unceasingly moving to a higher developmental manifestation. According to Navon and Goldschmidt (2010), many opportunities to optimize resources are missed due to the lack of real-time, up-to-date information. Labor, in particular, is a very important resource and it is very difficult to collect real-time data relating to its on-site performance. Measuring labor performance manually is labor intensive, inaccurate and error prone. This is why it is not done on a regular basis.

Bañuelas *et al.* (2006) believed that the prioritization of projects is determined by many criteria, such as a cost-benefit analysis or the Pareto priority index. But more and more construction projects are affected by poor technical quality and poor management teams. Rehabilitation and strengthening of reinforced concrete structures is a dynamically growing division of structural engineering. Strengthening of the reinforced concrete structures is one of the most difficult and important tasks of civil engineering. Individual approach to the problem is a necessity since any ready-made solution can be applied. One of the prime objectives is to provide detailed technical and cost-effective analyses (Kamiński, Trapko 2006).

It is therefore important to improve the performance quality which is very necessary for the construction industry. The Construction Industry Review Committee (2001) reported that although many quality management systems and philosophies (quality control, cost of quality, total quality management quality assurance) have been adopted and implemented by many organizations, serious problems can still be found on construction sites and the desired quality standard has not always been reached. Love and Li (2000) found that without an effective quality cost system in place, performance improvement can be very difficult to identify and measure. The quality of products or services does not only focus on their ultimate delivery, but also on the quality of the whole business process. Tam *et al*. (2008) said that, to provide optimum benefits, companies should apply the most reasonable and cost effective method to achieve client satisfaction. According to Enshassi *et al.* (2009), materials in project and availability of personnel with high qualifications strongly affect the quality performance of a project. Besides, the performance of the client is important because any decision made will affect project success. Failure on the part of the client might lead to stress factors causing significant problems in successive stages of the project. The client plays an important role in the procurement of construction activities and in the implementation of construction projects (Egbu, Ilozor 2007; Alinaitwe 2008). Therefore, the construction industry pursues a perfect management philosophy application to have an internal requirement for Six Sigma. Six Sigma was used in the manufacturing industry to reduce the wastes due to manufacturing process deficiencies. It is now used by almost all industries including the construction industry (Pheng, Hui 2004; Stewart, Spencer 2006; Han *et al.* 2008). For Bañuelas *et al.* (2005), Six Sigma has been considered a powerful business strategy that employs a well-structured continuous improvement methodology to reduce process variability and drive out waste within the business process using effective application of statistical tools and techniques. It is a quality philosophy at the highest level, relating to all processes, and a quality measure at the lowest level (Koch *et al.* 2004; Rajagopalan *et al.* 2004). Its programs improve operational performance in order to enhance customer satisfaction with a company's products and services. Schonberger (2008) and Chakravorty (2009) have pointed out that the objective of Six Sigma programs is to create a higher perceived value of the company's products and services in the eyes of customers. Six Sigma programs have performance metrics and measurements based on cost, quality, and schedules (Keller 2004). Six Sigma implementation uses a systematic procedure; a five-step DMAIC (Define, Measure, Analyze, Improve, and Control) methodology. Its principles are a problem-solving framework. In DMAIC each stage is based on a data analysis research. A detailed description of DMAIC methodology can be found in Pyzdek (2003) or Keller (2004). Project selection and prioritization is an important element of Six Sigma programs. Many studies in construction only focus on the DMAIC of the Six Sigma methodology. They did not mention the Design for Six Sigma process to design or to redesign process or quality. According to Harry and Schroeder (1999), the only way to surpass the five sigma quality levels is to redesign their products, processes and service by using the DFSS. But this approach is difficult to apply due to lack of data to support the claim and the absence of assumptions used to formulate it (Bañuelas, Antony 2004). It is difficult to evaluate whether their work is applicable in other industry than manufacturing. Design for Six Sigma (DFSS) is a systematic methodology based on Six Sigma for designing or redesigning products, services, or processes to meet or exceed customer requirements and expectations (Laudati 2007).While Six Sigma works to improve existing processes, DFSS starts at the early stage of the project, design, and development of products and services. The DFSS methodology uses a "roadmap" to guide the progress through each project. As written by Goffnett (2004), Schroeder *et al.* (2005), Zu *et al*. (2008), although there have been numerous case studies, comprehensive discussions, books and websites addressing Six Sigma, very little scholarly research has been conducted on Six Sigma and its influence on quality management theory and application. Especially in the construction industry, project managers must often face unexpected problems. The proposed solution usually cannot be followed as in the production phase. The management flow is influenced by many factors. The achievement of many works is very difficult to measure using explicit data. When evaluating achievement, and starting an improvement activity, the biggest obstacle is fuzzy data and materials. Therefore in the project management field, using Six Sigma management method competently is definitely difficult. The construction process is an outdoor activity that is affected by external conditions and is less repetitive than the manufacturing process. Simple and repetitive construction activities in which productivity is immediately reflected by the process variation factors helps to meet quantity for cost effectiveness (Han *et al.* 2008). The members of the construction team (architect, engineer and contractor) usually change with each project. In contrast to manufacturing, the product of construction (i.e. the built facility) is stationary, while the production facilities are mobile. The vast majority of individual construction firms is small and designs or builds are limited amount of facilities (Ilías, Søren 2000). How do we apply Six Sigma management methods in the construction industry to obtain a suitable and reliable quality improvement, cost, resources, time reduction and customer satisfaction? How to combine Six Sigma with finite element method?

## 2. Methodology

The goal of this study is to demonstrate the potential of applying Six Sigma to the construction industry. To attain this goal, a systematic methodology was proposed in this study. The proposed approach falls into three phases. The first step was to document the process, productivity and quality with relevant data through interviews with the company staff, Six Sigma black belt consultants, construction managers, engineers, clients and architects. Training materials, minutes of project meetings, management culture and presentations were collected and analysed in order to supplement the interviewee response.

The second phase is about DMAIC process. The goal of this phase is to improve and optimize construction process and quality based on five steps. The research has defined and applied the five steps according to the construction work process:

- Define: Organize goal clarity, state opportunity, form the project team, analyse SIPOC, recognize the current process.
- Measure: Define the measure indicators, collect data, seek for the variation source and determine the current process Sigma level.
- Analyse: Analyse process data, analyse the causes of potential problems, the nature and its impact.
- Improve: Identify problem-solving and process improvement programs, define new standards and assessment process.
- Control: Control method, review performance on a regular basis, expand the quality of follow-up, and improve process standardization and documentation.

After these five steps, the paper has conducted an evaluation to determine the Six Sigma Quality Level. If Sigma level is inferior to 6, then the DFSS procedure will be developed using the DCOV (Define, Characterize, Optimize and Verify) approach. The third phase is the DCOV. The goal of this phase is to avoid, to prevent defects since the prefabrication of composite components (beams, floor, etc.) and to redesign when the expected Sigma level is not reached. The four steps of the DCOV are:

- Define: Describe project objectives, compose multi-functional design project team, collect customer requirements and define project objectives and processes.
- Characterize: Propose and screen concept for the technical requirements in accordance with the concept of steel-concrete beams and then establish preliminary design.
- Optimize: Conduct optimal design and implement process documents and product life-cycle cost-optimization. Monte Carlo simulation is used in this phase on a computer to simulate the production of steel-concrete beams according to the initial design and simulation of different design elements in the scope of their respective values. The risk analysis software OptQuest of Crystal Ball tool is used to optimize steel-concrete beams design. The finite element (ANSYS) model is then established in order to verify the technical and scientific requirements of proposed model and to be able to compare the results to the case study one.
- Verify: Verify process and product quality, and then finish the requirement document. The feasibility is validated and the scorecard tools are used to record the process capability indicators of the pilot production. The model provides a methodology for quantifying the changes required in a design or redesign to meet the desired performance outcome.

This paper focuses on the following objectives:

- investigate construction process and quality problems in construction;
- review the theory of Six Sigma in construction industry;
- apply prefabricated composite structure combined with Six Sigma;
- redesign steel-concrete components using DCOV;
- show the effectiveness of Six Sigma in improving construction process and quality.

In order to prove the validity of the developed model, a real case study based on construction quality and process is presented to resolve concrete cracking and slippage problems. The approach is then applied to steel-concrete composite structure to improve construction process and quality and to reduce construction materials. Three composite steel-concrete beams were tested by investigating their strength and crack limit by using finite element method. It combines composite structure system with finite element method (ANSYS) based on Six Sigma management in order to produce high quality construction projects and to prevent construction failure. Comparisons between the finite element results and experiment results have been conducted. An economical and high quality prefabricated composite beam model is proposed.

The application of Six Sigma to improve construction process and quality and to reduce the reworks of the main structure based on statistical analysis during construction is explained.

## 3. Construction process management model

The construction industry is one of the most complex industries. The quality of the engineering process plays a pivotal role in the production of a high-quality construction product. This issue is increasingly gaining consensus. However construction engineering is a very strong creative design labor result. The construction process involves human input, methods, tools, management and many other aspects. The other stage of the construction life cycle, like the design, code and other links influence the existing factors of construction quality. But when the construction bug is found late, the rectification price will be high. Modern quality management puts emphasis on the quality during the process, rather than testing the product processes. If we aim to improve construction quality, design process quality must be enhanced.

Therefore, improving only the quality of the project is not enough. We must also make continuous improvement to the entire construction development process, discover in time process quality problems, and eliminate problems before they occur. Six Sigma management is just such a system. It focuses on the process resulting in continuous improvement. From the researches of Pheng and Hui (2004) and Schwalbe (2006), in Six Sigma, the definition of quality is broadened to include economic value and practical utility to both the company and the customer. In the process of construction industry projects, Six Sigma is a quality management theory.

The purpose of project quality management is to ensure that the project meets its requirements by applying the theories of Six Sigma, which does not consists not having defect, but pursues the perfection. It has a fixed position, a production flow, various structures, various quality requirements, various construction methods, high integrity and long construction cycle. Harry and Schroeder (1999) have used the DMAIC method to conduct the quantification of construction flow analysis and found the most essential factor to improve.

Six Sigma management DMAIC flow utilizes statistics and quantitative methods. It explores the process and identifies errors and defects. It uses powerful analytical tools of quality management to carry out the system analysis of problems and the exploration of the causes of problems. Thus the DMAIC urges the organization to take improvement measures promptly to enhance the entire process of quality.

Before the team starts to operate, the DMAIC project regulation must first have the authorization of project initiators and other senior leadership. As a benchmark achievement activity of the define phase team, the project regulation has directly reflected the quality of the project team activity, directly related to the project progress and DMAIC process implementation.

The define phase must set up the implementation of the project team of the DMAIC construction process flow.

Although the control stage is the final stage of DMAIC flow, the project team must maintain the key stage of its construction process improvement results so that after the construction optimization process, it can maintain stability, predictability, and conform to the client's requirement. The project team needs to establish the document surveillance process, a formulation process management plan, to consolidate the realized achievements. At the same time, the process change must be paid attention to. The measurement and monitoring have to be continually carried on. The process corresponding adjustment has to be carried every time the customer needs a change. According to Zhao *et al.* (2008), Six Sigma quality management tools and methods are important supports. Application of these tools and methods can help organizations to improve the efficiency of identifying problems and analysing the causes. In order to holistically improve construction process quality, a process modeling based on DMAIC and DCOV is established and shown as following in Fig. 1. The model is divided in two main parts: the DMAIC (Define, Measure, Analyse, Improve, Control) to improve the problem identification and analysis performance, the prefabricated composite components construction based on DFSS which has used DCOV process for design optimization and prevention of errors.

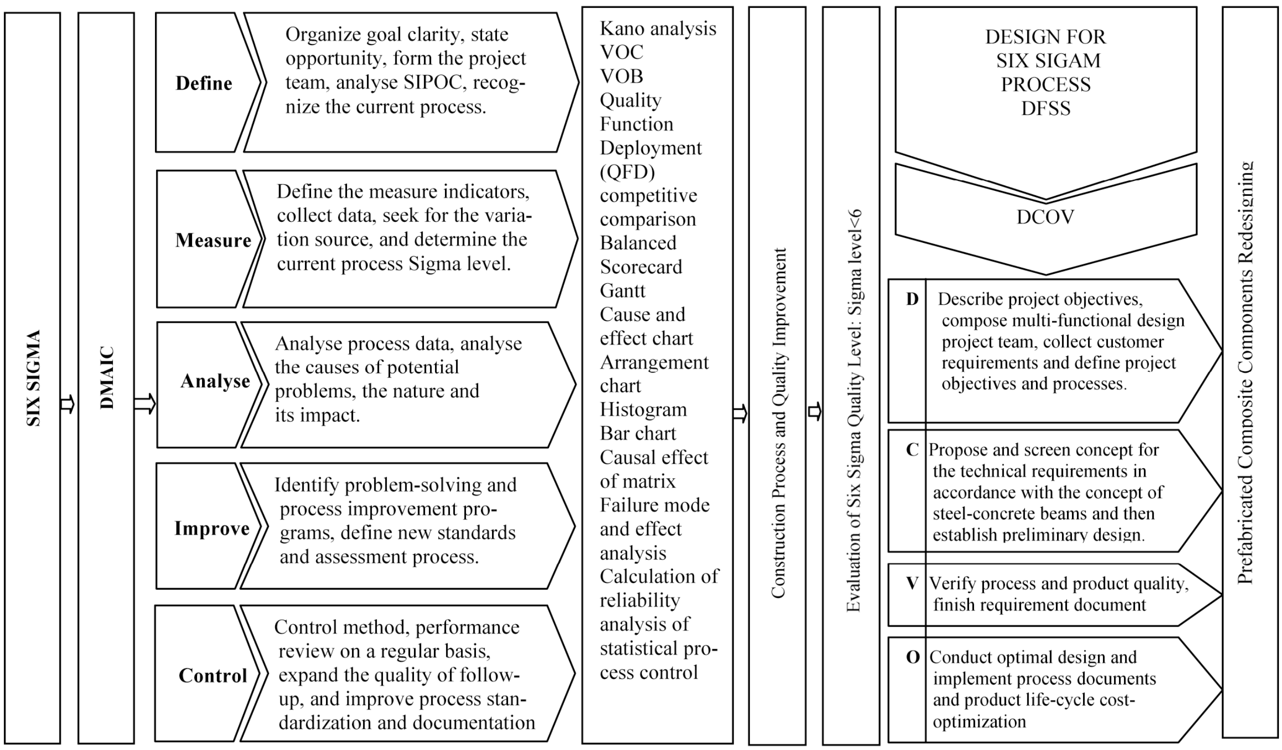



**Fig. 1.** Construction industry process management model

## 4. Case study

The design of specimens (ZL1, ZL2 and ZL3) for the experimentation is referenced to a prototype of steel reinforced concrete beams of Xin-chun building in Tianjin (China). The test beams are in rectangular section of 120×240 mm and a span of 3300 mm. Tianjin Xianyi Construction Technology Co. Ltd., according to the specimen model design drawn, produced concrete beams and steel beams which were sent to the structures laboratory of Tianjin University. Six Sigma methodology has been divided into five stages to realize project quality optimization and to enhance customer satisfaction. In this project, Six Sigma quality management theory analysis (FMEA) method has been applied. Various quality problems have been analysed through the quality production process. This research, after adopting the design and technical correction measures, finds out the factors which influence the project quality and the reliability of potential quality problems. It improves the project product quality and resistance to various performance characteristic abilities. In view of the project characteristic, it carries on the control improvement of the key technique which affects the composite structure quality to realize an excellent construction, in order to enhance the satisfaction of customer. The construction shows cracks in the steel reinforced concrete composite beams development situation, and steel reinforced concrete composite beam failure modes.

During the experiment, the location of the supports and cross-arrangement of dial indicator measuring specimen deflection were at 650 mm from the end of beams. There is also the sample layout dial gauge measuring the interface slip.

Furthermore, in this project, the paper applies the FMEA method of Six Sigma quality management theory. The quality control process method is often referred to as D-M-A-I-C.

### 4.1. Process for implementation of Six Sigma management method in construction industry

***Define***

According to the quality survey standards of the produced concrete, three specimens of steel concrete beams have been selected for research analysis, using statistical methods. Quality problem tests were also conducted and the summarized data are shown in Table 1.

Reinforced concrete structures are being used much more during constructions. The entire construction quality, the structural security, construction cost as well as customer satisfaction depend on the concrete quality. Steel and concrete have been intensively and extensively used as structural materials for bridges, buildings, and the other structures, in civil and architectural engineering. The theoretical analysis of the actual behavior of modern structures from high strength concrete and steel are more frequently employed during design, realization and the utilization of building structures. The combination of steel-concrete materials gives rise to the occurrence of special phenomena whose influence on structural reliability isn't at present commonly implemented in design (Kala *et al.* 2010; Gailius, Kinuthia 2009).

Construction process also influences time and cost. Therefore during construction enough attention must be paid to concrete quality and to the construction process. Due to the fact that in construction customer requirements are variables, the Quality Function Deployment (QFD) method has been applied to transform the customer request into the technical and quality control request. The deployment method has been taken according to the quality function of the customer requirements. To preserve construction integrity, concrete quality objectives will be to guarantee that cracks and slippage won’t appear. To avoid damp and to preserve the building integrity, concrete quality objectives are to guarantee that no leakage will appear. Currently, the construction process in this industry is still traditional, with labor intensive in situ construction techniques. That implies a lot of material (cement, sand, gravel, etc.) waste. This kind of condition increases the economic cost of the enterprise and affects the level of confidence of the enterprise. Quality management and control is not rigorous, construction quality is poor with attendant high costs. Strengthening various stages of control of the construction process will guarantee that all the components satisfy the prerequisite conditions as design demands. That will control the quality efficiency; and improve the processes which are essential to the development of the enterprise. Therefore a fundamental analysis must be done to determine and to control the factors which affect concrete crack, slippage between concrete and steel.

The main Six Sigma team is composed of: team members, client, Black Belts, Green Belts and other members: organizations which improve implementation measures and data collection.

**Table 1.** Analysis of quality problems

| No | Defect | Cracks quantity | | |
|---|---|---|---|---|
| | | ≤ 0.1 mm | ≥ 0.1 mm | Accumulated cracks |
| 1 | Cracks produced by bad mix proportion | 4 | 11 | 15 73% |
| 2 | Surface shrinkage cracks | 2 | 4 | 6 80% |
| 3 | Dehydration cracks | 2 | 3 | 5 86% |
| 4 | Improper strength concrete poured, durability | 4 | 4 | 8 88% |
| 5 | Improper maintenance techniques | 3 | 2 | 5 95% |
| 6 | Other reasons | 3 | 6 | 9 100% |
| | Total | 18 | 30 | |

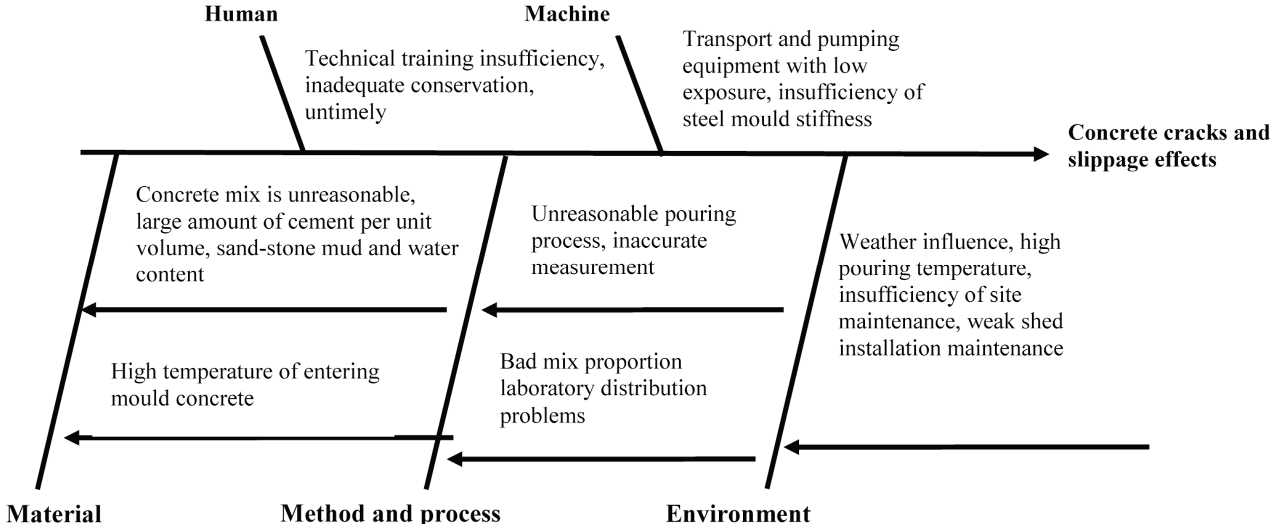



**Fig. 2.** Cause and effect diagram (CE)

### *Measure*

The measure stage goal involves the choice of quality characteristics to determine the critical to quality (CTQ), to define the standard results and to measure the system analysis.

According to the site construction investigation and based on statistical method, some specimens have been selected to conduct analytical studies by using statistical method. The statistical method adopts the cause and effect diagram (CE) in Fig. 2. This paper carries out construction process and quality improvement analysis using prefabricated composite structure based on Six Sigma.

The process monitoring method is defined, the data are collected and all the problems are found. The statistical crack damage frequency and slippage damage are found. This paper:

- analyses prefabricated composite beams quality problems;
- investigates the current raw material control method through site control and related person interview;
- conducts the statistics and analysis of composite concrete cracks and slippage;
- analyses the reasons why the mix ratio test is insufficient;
- utilizes finite element method (FEM) to propose an appropriate model.

### *Analyse*

During the prefabricated composite component production process, the component appearance quality is not stabilized. There are more shrinkage cracks, slippage and other problems as enumerated in Table 2.

Through investigative analysis and based on Table 2, the prefabricated composite component shrinkage cracks, slippage, and smoothness occupy a larger part of quality problems, followed by interface connection and comprehensive reflection for appearance quality problems.

The analysis stage includes the establishment of process capability and definition of the end results.
Through the five aspects for which the measures have been utilised, the application of brainstorming conducts the analytical study of the reasons and degree which affect concrete quality (see Table 3).

According to the key prefabricated component appearance quality problems and through the system analysis diagram (Fig. 2), the main causes of quality problems have been found.

From the analysis of the quality control of prefabricated composite components main reasons are as follows:

- insufficiency of technical training;
- insufficiency of steel stiffness;
- some problems with laboratory test;
- some problems with the entering field material control;
- the establishment of work shed maintenance;
- unreasonable concrete mix;
- weather and temperature influence.

**Table 2.** Analysis of quality problems

| Inspection project | Sampling inspection quantity | Rejection number | Unqualified frequency (%) | Cumulative frequency (%) |
|---|---|---|---|---|
| Shrinkage cracks | 1250 | 48 | 41.8 | 42.8 |
| Smoothness | 1250 | 31 | 23.6 | 76.4 |
| Components size( ±4 mm) | 1250 | 22 | 18.6 | 91.0 |
| Component strength | 1250 | 11 | 6.4 | 95.4 |
| Slippage effects | 1250 | 36 | 25.7 | 97.3 |
| Interface connection | 1250 | 25 | 19.89 | 98.1 |
| Total | 1250 | 173 | 100 | 100 |

**Table 3.** Reasons and degree which affect concrete quality

| No | Reasons | Impact on concrete | Impact on composite beams |
|---|---|---|---|
| 1 | Technical training insufficiency, inadequate conservation, waiting time | high | high |
| 2 | Transport and pumping equipment with low exposure, insufficiency of steel mould stiffness | low | low |
| 3 | Unreasonable concrete mix is, large amount of cement per unit volume, sand-stone mud and water content | high | high |
| 4 | High temperature of entering mould concrete | medium | medium |
| 5 | Unreasonable pouring process, inaccurate measurement | high | high |
| 6 | Bad mix proportion, laboratory test distribution problems, inadequate cooling step | high | high |
| 7 | Weather influence, high pouring temperature, insufficiency of site maintenance, weak shed installation maintenance | medium | medium |
| 8 | Interface connection, application of chemical anchors | low | high |

Through the concrete quality problems and the slippage, we conduct an analysis (FMEA), measurement and find that the key problems which affect the concrete crack are the cement variety, the mix proportion of concrete, the admixture, the construction technique, disposable formation as well as the maintenance conditions.

### *Improve*

In view of the above analysis of concrete crack and slippage problems, through reasonable measures and methods, the following measures have been adopted.

When selecting concrete raw material, the coarse and suitable aggregate must adopt a continuous grading; the fine aggregate adopts the medium sand suitability. The concrete joins the retardant, the water reducer, the slag powder and so on, to reduce the cement volume dosage. The hydration heat used on the cement should be as low as possible and adopt long setting time cement. During construction, the paper either discharges leakage or facilitates mixing of dry and hardened concrete where leakage occurs. Construction continues when this operation is complete.

The prefabrication system uses equipment of proportioning and mixture controlled by computer. Additives are added in order to obtain specific mechanical performances. The placement and compaction of concrete are performed with suitable equipment. Protection is provided when climatic conditions are unfavorable.The quantity of mixing water is reduced to its strict minimum and the compaction as well as the curing of the concrete is carried out using controlled systems. The resistance of the concrete can thus be adjusted with precision to the specific applications for which it is intended.

If the workers are inexperienced, machinery is used for prefabrication. The skills of the technical director and the production chief are not at the required level. So training and site visit will enhance the technical operation experience. The provision for training and education among staff and involving employee participation are more effective approaches in implementing waste management (Shen, Tam 2002; Lingard *et al*. 2000).

The use in exchange of manganese steel to replace the ordinary carbon steel and the manufacture extrusion steel is changed into a rigid mold.The research improves the laboratory control at the work site and analyses the reasons why the mix ratio test is inadequate. The best mix proportions are presented in Table 4 and help to guarantee that the mix ratio of the prefabricated concrete is satisfactory.

**Table 4.** The best mix proportion

| Mix proportion | Sunny times (sand-water content 4%: Stone powder water content: 3.5%) | Rainy times (sand-water content 6.5%: Stone powder water content: 6%) |
|---|---|---|
| C15 | 1:1. 976:3. 209:0.186 | 1:2. 024:3. 286:0.061 |
| C20 | 1:1. 726:2. 939:0.194 | 1:1. 768:3. 010:0.082 |
| C25 | 1:1. 539:2. 608:0.203 | 1:1. 576:2. 671:0. 103 |

The moisture and water contents of the sand and gravel are controlled to avoid reduction of concrete cohesive force. The paper also works to avoid the water content which can influence the mixture water-cement ratio and controls the mud impurity contained in the sand and gravels.

Ventilation and conservation of the environment of the prefabricated elements have been improved. The paper allows an extension of work shed, meets the required conditions for prefabricated product stack, and avoids a high temperature exposure that can create cracks. The quality of prefabricated products is not influenced by environmental factors. Concrete prefabrication offers many more answers to the requirements of suitable construction than the other methods of construction.

The study of Arditi and Gunaydin (1997) and Tam and Le (2007) have shown that quantities of resources are wasted each year because of the inefficient or non-existent quality management procedures.

### *Control*

The goal of the control stage is to guarantee the process improvement and not let the situation revert to the previous situation.

The quality control of prefabricated composite components is based on a system of self-checking under the surveillance of a third party. The control of the production in factory includes regular procedures, instructions, inspections, tests and the use of the results for equipment control, raw materials and other materials, production process and products. The results of the inspections are included in registers put at the disposal of customers: (a) the concrete compressive strength is determined based on the 28-day compressive strength prior to any evaluation. The approved concrete strength is achieved using mathematical statistics method and must be conformed to qualified requirements; (b) the components have to be smooth, dense and solid, with no voids and warped appearance; (c) the exterior size of construction is within allowable design specifications.

After the implementation of all measures, the quality testing investigation indicated: the implementation improvement measure, the extrusion forming component in various cracks, distinct improvement of the smoothness and the component size aspects, achievement of the expected effects (Table 5).

**Table 5.** Analysis of the investigation results

| Inspection project | Production quantity | Qualified quantity | Rejection number | Qualified rate (%) |
|---|---|---|---|---|
| Shrinkage cracks | 1250 | 1230 | 20 | 98.6 |
| smoothness | 1250 | 1244 | 6 | 99 |
| slippage | 1250 | 1246 | 4 | 99 |
| strength | 1250 | 1244 | 6 | 99 |

After strengthening the control goal, consolidating the achievement, we guarantee that the improvement will be maintained and the slippage will not be high, the concrete crack will not exceed 0.2 mm. This helps to improve the project quality and enhances customer satisfaction.

## 4.2. Process implementation of redesigning steel-concrete components using DCOV

After adopting Six Sigma approach, we found that the Six Sigma levels were not reached. Then the paper decides to redesign processes and the steel-concrete beams. In order to produce high quality construction through continuous improvement implementation, products, processes and services were redesigned by applying DFSS to surpass the five sigma quality levels. It studies Design For Six Sigma model, combines steel-concrete beams materials design and production characteristics and proposes a unique design model of steel-concrete beams.

DFSS, a non-defect product and process design method, is based on concurrent engineering ideas. It takes full account of customer needs from the earlier stage, using system approach to solve problems, to realize product/process design robustness. Then it improves quality, develops speed and reduces product life-cycle costs. It helps to solve product and process design issues. DFSS common models include: DMADV, IDDOV, ICOV, etc. Although these models are varied, each has its features, but the basic idea is similar. They take design process as the main thread. Each step uses system approach to optimize, evaluate, and reduce design defects and changes. According to the design characteristics of steel-concrete components, we summed up suitable design for DFSS model using the DCOV which is Define, Characterize, Optimize and Validate.

### *Define*

The main task of the Define phase is to describe project objectives, compose multi-functional design project team, collect customer requirements and define project objectives and processes. It determines the scope of the project and starts the project. Analyse important points and difficulties of product and process design of steel-concrete components.

*Project objectives*

The objective of this project is to develop prefabricated steel-concrete beams which satisfy customer requirements in a competitive market under existing production equipments conditions (specific price, parameters, etc.). The research designed and constructed reinforced concrete beams. In the laboratory, chemical anchors and bonded steel technology were used to link the concrete and steel beam to form a composite beam. Since then, the laboratory has completed a follow-up of paste work using strain gauges. The sectional form of the reinforced beams is shown in Fig. 4.

*Customer requirements analysis*

Starting from project quality requirements, this paper first identifies functional requirements of customers. Then it links up the functional requirements with products or service characteristics and further identifies the project product or service technical parameters according to functional requirements and product characteristics

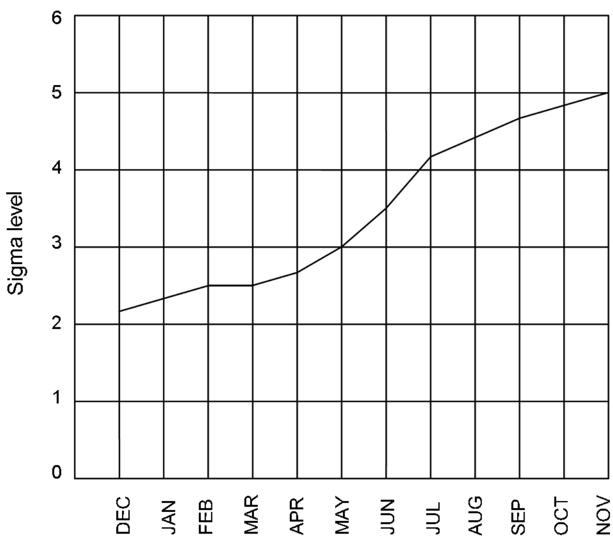



**Fig. 3.** Sigma level of the current process

relation matrix, as well as the correlation between product characteristics matrix. Through quality planning, the technical parameters of the design specifications are identified.

The data of prefabricated component problems are collected during 12 months. The statistical results of the Sigma level are shown in Fig. 3.

*Determine project scope*

SIPOC tools from a macro point of view describe and examine the organization's processes and guide the team members to improve the attention focused on the scope limitation in order to avoid unnecessary expanded project study scope. SIPOC tools application can determine the project study scope of steel-concrete beams development as new product development process, namely, product design and production process.

***Characterize***

The main purpose of characterize phase is to propose and screen concept for the technical requirements in accordance with the concept of steel-concrete beams and then establish preliminary design.

*Conceptual design*

The performance of steel products is determined by its internal microstructure decision to meet the required yield strength. There are three possible structural designs. We select the composite beam design using concrete, reinforced bar and steel beam.

Material performance test provides the theoretical analysis of necessary material parameters. The follow-up analysis was important. The test material is divided into three parts, sheet steel beams, steel bars and concrete.

*Proposed design parameters*

According to the conceptual design conclusions, we determine the ideal steel-concrete structure, while the structure of steel products (reinforced bars and H steel beam) depends on the ingredients and process decisions. We use brainstorming tools to determine the composition design and technological design of prefabricated steel-concrete beams.

*Proposed process parameters*

Product design parameters are decided by the process control parameters. According to the design parameters of steel-concrete beams, we use brainstorming tools to determine the steel-concrete beams process parameters.

*Proposed preliminary design*

According to the conceptual design of steel-concrete beams, we select composite products with same strengthening mechanism, but the performance indicators requirement is below to the one required to conduct the regression analysis of historical data. Based on the principle that $P < 0.05$, the paper obtains the performance transfer function.

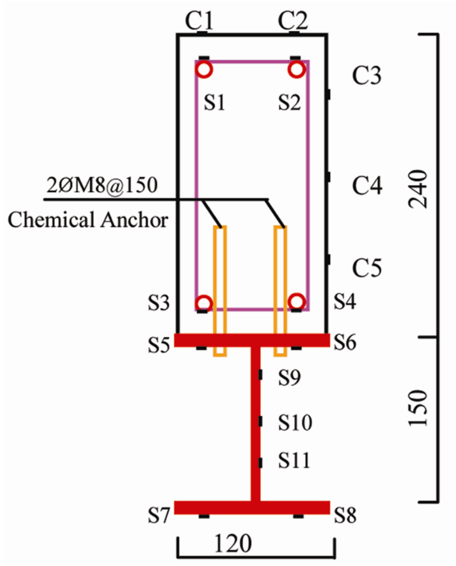



**Fig. 4.** Specimen section strain detail location

This in order to obtain required performance indicators of steel-concrete beams, namely, to increase the yield strength, compressive and tensile strength without reducing elongation index. According to mature product design, we propose preliminary design steel-concrete beams (see Fig. 4).

***Optimize***

The main objective of optimization stage is based on the determined transfer function of the previous stage to conduct optimal design and implement process documents and product life-cycle cost-optimization.

*Monte Carlo simulation and pilot production*

Monte Carlo simulation is used on a computer to simulate the production of steel-concrete beams according to the initial design and simulation of different design elements in the scope of their respective values. When the critical performance factors changes, Monte Carlo simulation verifies the feasibility of the initial design. The most important is that it reduces the risk of industrial pilot production. The initial design can satisfy the requirements. However, the performance indicators of process capability still need to be improved. According to the preliminary design of small-batch pilot production, we obtained steel-concrete data, and revise the performance transfer function, to obtain steel concrete beams performance transfer function.

*Optimal design*

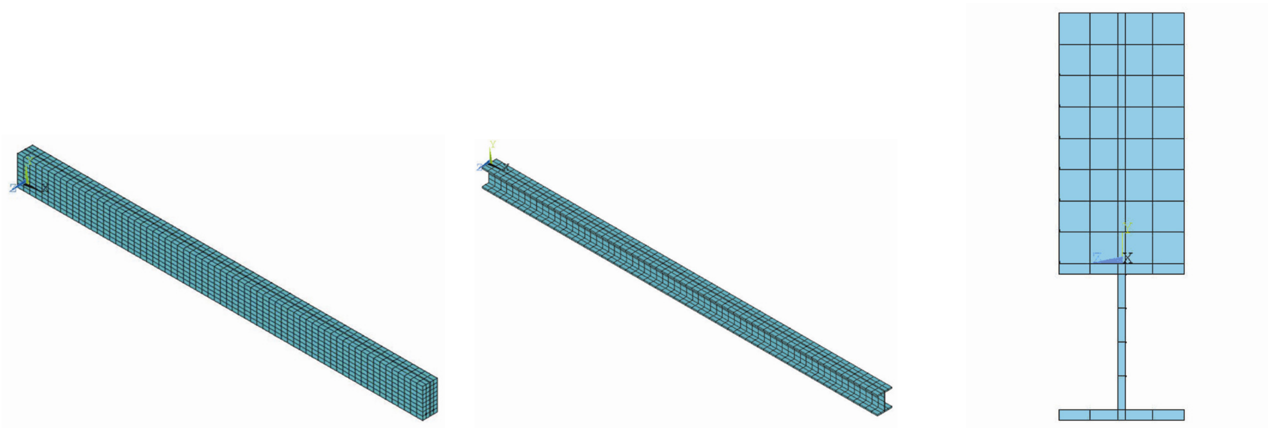
The risk analysis software Opt Quest of Crystal ball tool is used to optimize steel-concrete beams design, this principle is based on the minimum of whole scale of mixing elements principle (lowest cost). The software finds a reasonable combination of different composite elements, and implements performance indicators to meet the design requirements. At the same time, it gives the target value and tolerance of design elements. Finally, we obtain steel-concrete final design, performance indicators for process capability scorecard.

According to finite element model mesh features, the finite element analysis model for ZHL1–ZHL2 is selected at 600 mm from the end of the anchor bolts data, the model ZHL3 is selected at 550 mm. Reinforced concrete and H Steel Beam respectively uses SOLID65 and SOLID45 entities unit to establish an independent separate model, as shown in Fig. 5.

The boundary conditions constraints and loading beam model status of finite element analysis process are shown in Fig. 6.

***Verify***

According to the optimized design, the research has conducted construction pilot production to validate its feasibility and use the scorecard tools to record the process capability indicators of the pilot production. The results showed the optimized steel-concrete beams performance stability and the process capability sufficiency. This study identifies potential needs of customers such as welding performance and fatigue performance which are very regulatory test items. It uses commission inspection qualification of random sampling of testing detection of third-party.



a) Concrete Model b) H Steel Model c) The whole cross-section model

**Fig. 5.** Shaped steel-concrete composite beam modelling

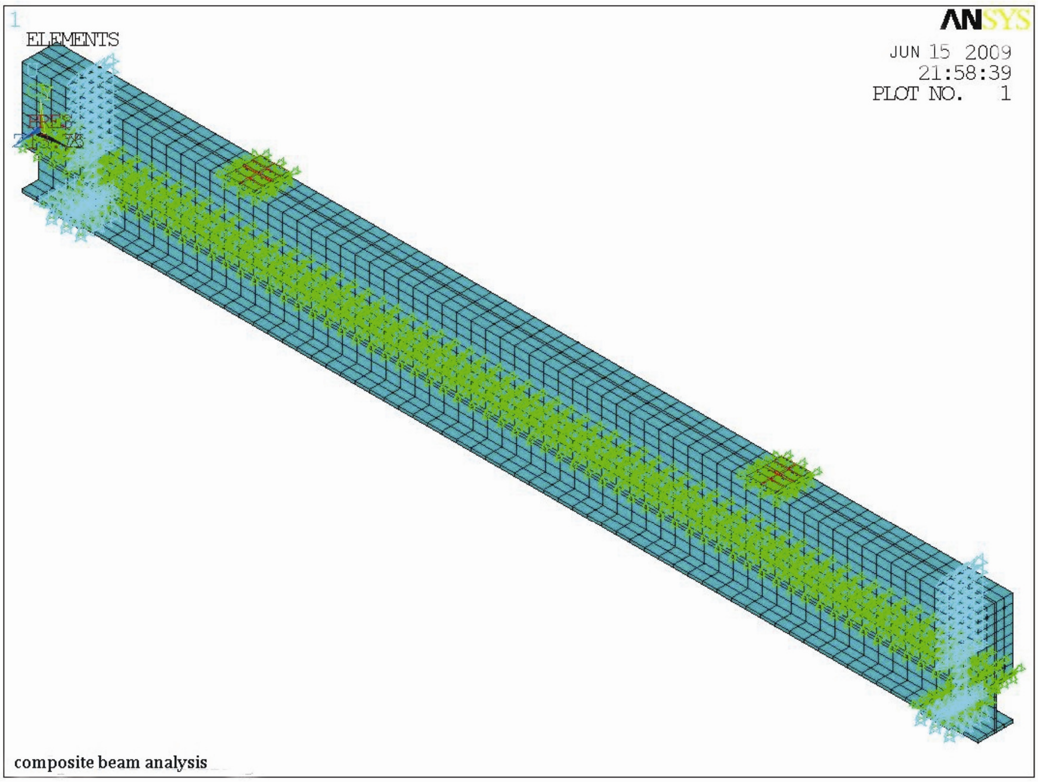



**Fig. 6.** Finite element analysis of H shaped steel-concrete composite beam

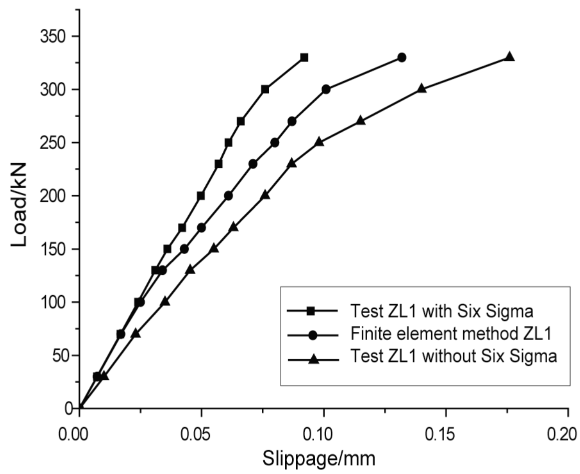



**Fig. 7.** Load-slip curves 1

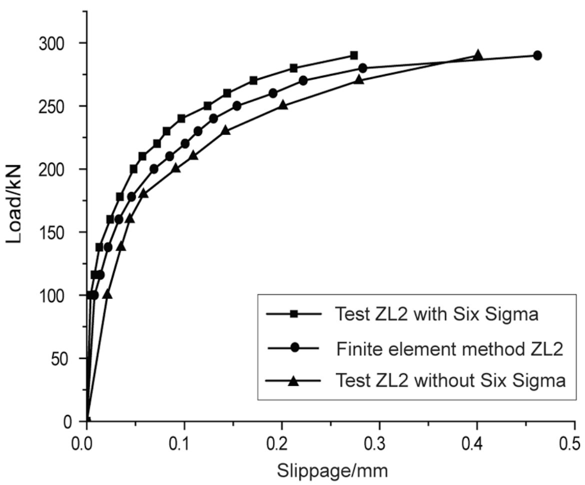



**Fig. 8.** Load-slip curves 2

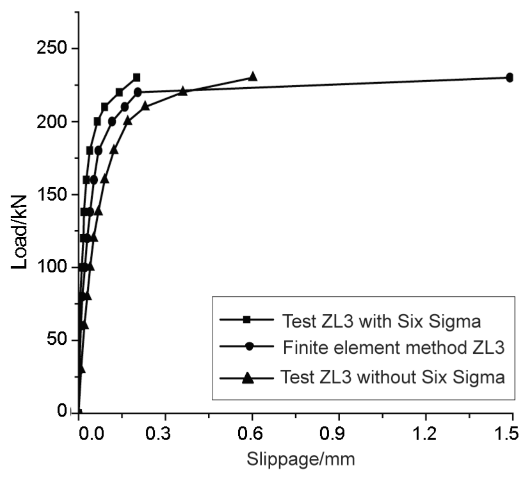



**Fig. 9.** Load-slip curves 3

During the early stages of specimen ZL1–ZL3 model experiment process, measure of interface slip of H-beam-concrete composite is conducted, and recorded during loading process, the location and the interface slip value. In the finite element (ANSYS) model of beam post-processing, the interface is selected through the spring unit and view during the entire loading process unit slip value under arbitrary load. We define the appropriate unit to extract the corresponding data table, draw at any desired location the load-slip curve, the interface of the relative slip along the beam cross-distribution curve, in order to analyse slip characteristics. Then we draw the load-slip transfer comparison curve as shown in Figs 7–9.

## 5. Discussion of the results

The specimens ZL1 and ZL3 failure under positive moment began to receive the crushed concrete compression. This time the plasticity development of the steel beam is not yet obvious, and the specimen failure has certain suddenness.

The concrete of specimens ZL2 under negative bending is in tensile deformation, cracks appeared earlier. With the increase of load, crack develops, the concrete gradually withdraw work, and the specimen bending moment is mainly bear by the reinforced bars and concrete.

Because the point is more dispersed, the phenomenon is not obvious, but then we can see that the reinforced bars strain in the middle of concrete slab is bigger than the reinforced bars strain in the concrete slab edge. It is visible that steel beams and concrete slab work together, but because of shear lag effect, strain of reinforced bars in the concrete slab varies with position. But although close to the ultimate load, the longitudinal reinforced bars in slab edge work well.

It can be seen that the strain distribution showed changes in wave shape (ZL2). The reason is because concrete slab surface cracks, span multi cracks, caused by the randomness of cracks. Although close to the limit load, the edge of the plate concrete nominally participates and work well. Although being involved in the whole cross-section flexural.

The comparison of specimen bearing capacity before and after strengthening based on Six Sigma shows that the shear carrying capacity after strengthening the reinforced concrete composite beam specimen based on Six Sigma compared to the one before (without Six Sigma) has substantially improved due to the concrete part quality. But not the whole cross-section steel beam web yield. Therefore, the shear bearing capacity of reinforced concrete beams before strengthening and the one after strengthening when cracking occurs have been compared, as shown in Table 6.

Steel reinforced concrete composite beam specimen load-bearing capacity has greatly increased than before strengthening concrete beams. The comparison of flexural bearing capacity before and after strengthening is shown in Table 7. In the table, $M_u$ is based on the actual strength of materials to be substituted into the standard to obtain concrete beam flexural capacity.

**Table 6.** Comparison of specimen shear capacity before and after strengthening

| Specimen | Shear bearing capacity (kN.m) | | |
|---|---|---|---|
| | Before strengthening $V_u$ | After strengthening $V_u^s$ | $\frac{V_u^s - V_u}{V_u^s}$ |
| ZL1 | 66.3 | 165 | 1.49 |
| ZL2 | 50.3 | 150 | 1.98 |
| ZL3 | 46 | 120 | 1.60 |

Note: $V_u$ is shear bearing capacity of concrete beams before and after strengthening; $V_u^s$ expresses the cross-section shear bear when steel reinforced concrete composite beam is broken.

**Table 7.** Comparison of flexural bearing capacity of specimen before and after strengthening contrast

| Specimen | Flexural bearing capacity (kN.m) | | |
|---|---|---|---|
| | Before reinforcement $M_u$ | After reinforcement $M_u^s$ | $\frac{M_u^s - M_u}{M_u}$ |
| ZL1 | 14.8 | 100 | 5.76 |
| ZL2 | 14.8 | 135 | 8.12 |
| ZL3 | 13.6 | 112 | 6.42 |

Note: $M_u$ in Table 7 is concrete beam flexural bearing capacity before and after strengthening; $M_u^s$ is the biggest moment of the section when strengthening concrete composite beam is broken.

Test data shows concrete beams through the shear connector with steel beams combination. The composite beam shear and flexural capacity have increased compared to the original concrete beams. And the flexural bearing capacity has increased more than the shear bearing capacity. Therefore, the composed beams after strengthening may appear "strong bending weak shear" condition. Analyse steel reinforced concrete composite beam shear properties has great significance.

A three-dimensional finite element model can reflect reinforced concrete slab of the beam, stud shear connectors and steel beam geometry properties and material nonlinear work situation. In order to show that the nonlinear analysis of composite beams bring all degree of the shear connection number, the action of concrete slab when analysing reduce the space between analysing and bending and shear strength has been taken into account.

The maximum ultimate shear strength provided by the finite element analysis results is 786 KN. The 1996 AS2327 standard specifications maximum ultimate shear strength is 439 KN. The maximum shear strength of composite concrete slab has increased of 80%. The vertical shear strength of composite beam increases as soon as the degree of shear connection increases. Based on experiments and nonlinear finite element analyses, the concrete slab combined with composite action has great impact on the vertical shear strength of composite beam. Liang *et al.* (2005) also came to a similar conclusion on their study.

All different shear force combinations obtained from the finite element analysis influent next ultimate shear strength of the composite beam. We can see that the vertical shear strength follows shear force combination increase and decrease, which also confirmed by the research experimental findings of Donahey and Darwin (1988). This indicates that the composite beam arranges sufficient shear connector.

We can see that the vertical shear strength of the composite beams for arranged shear connector is higher than the one which does not have composite effect. From three groups of test beams and the corresponding finite element model beam curve comparison, the following features are obtained:

- in the initial loading, interface slip and load showed similar straight line. Sliding and the load growth were slow. When the load reached their limit after more than 70%. Non-linear characteristics began to appear and the slippage suddenly becomes large. The growth speed significantly is faster than the load. After reaching the limit load of 90%, the sliding rate growth achieves the maximum of amplitude as shown in Figs 7–9;
- because of site test conditions characteristics, the measurement of both right and left side of simple beam sliding data is different. The finite element model of beam entity model and the loading conditions are strict symmetrical in order to have the same result for cross-axis on both sides. It can be seen that through the curves comparison, slippage curve of the finite element and all experimental measured results curve results trend are similar (Figs 7–9). The slippage in the interface H steels-concrete increases with the load but remains low throughout the test, mainly because of the high density of studs: 0.1–0.8 mm maximum in the elastic and the plastic range. To ensure sufficient joint action between H plate steel and concrete, shear connectors must be installed in areas of introduction of concentrated loads. The key problems which affect the interface sliding are: used glue, chemical anchor, shear connectors, concrete smoothness and construction techniques.

Based on the finite element model of beam ZHL1–ZHL3, the location of the selected sliding, the interfacial slip was measured. Through curves comparison, under the same load, finite element slippage is greater than the amount of the experimentation value but smaller than the one with Six Sigma. This basically is conformed to the theory: the more the distance between the beam extremity and the position where load is applied is closer, high is the slippage. The gap slippage on both sides of the cracks increases throughout the test. This is shown in Figs 7–9.

The Design brings full mobilization of shear steel beams and concrete flange in the middle of the steel-concrete composite beam can enhance the shear strength compared with steel beams. Composite beam with shear span ratio is 2.0 or less, more fragile occurred shear failure. Ignores concrete shear Distribution Conservative approach of testing, confirmed that the current specification underestimated the shear strength of composite beams, due to this fact. The model provides a good estimated value for shear strength of concrete slab. Only when under the positive moment, the effective shear zone of composite cross section only has a small amount of longitudinal reinforced bars. It is expresses by connecting the composite beam with regular plate stud pull out strength force.

The proposed model design strength and results with finite element analysis results and under Six Sigma effect are compared. We can see a difference between the experimental value of design model and finite element analysis results.

The results showed that the steel-concrete beams fully meet user's requirements and ensure that the production volume is controlled according to the optimized design. From the comparison between the estimated data of the model and the obtained data of the experimentation, the benefit gained from the model has been discussed. A certain extent reflects that the finite element model of this paper can be referential, can be used as a pilot based on an effective complement to theoretical analysis.

From the case study, it clearly illustrated that a huge amount of wastage can be reduced after adopting prefabricated composite structure based on Six Sigma. The application of prefabrication based on Six Sigma provides enormous advantages, such as improved quality control, reduction of construction time (26.2%), construction waste (67%), contribution to a clean environment. A huge amount of wastage can be reduced after adopting prefabrication. Up to 84.7% materials waste can be saved. But a redesign of process and product is necessary to obtain a high Sigma level.

## 6. Conclusions

Prefabricated composite structure design based on actual engineering prototype and related test theories is combined to the notion of six sigma management in order to obtain better application results.

Six Sigma centers on improving project by improving process, analysing and selecting project as well as to compose the project team. It also request strictly to implement DMAIC process model, to guarantee improved results, to demonstrate its validity through each project result. Six Sigma objectives depend on continuous improvement of the project through data so as to realize the management effects. Construction enterprises should realize the feasibility and importance of this theory and method. Generally, the application of Six Sigma principles to establish a quantitative and qualitative construction engineering quality system may increase the cost. But from the perspective of long-term benefit, applying Six Sigma management increases quality management.

The composite structure prefabrication offers many more answers to the requirements of suitable construction than the other methods of construction. The application of Six Sigma help to reduce the consumption of energy during construction, pollution, noise pollutions, waste and to develop new ideas and strategies of durability during the complete life cycle of a building in the context of sustainable development. The results show that this approach is feasible in construction quality management and has certainly significance to the construction company's implementation.

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## PROCESO TOBULINIMAS IR KOKYBĖS GERINIMAS STATYBŲ SEKTORIUJE TAIKANT „ŠEŠIŲ SIGMA“ METODĄ

**F. M. Tchidi, Z. He, Y. B. Li**

S a n t r a u k a

Statybų sektoriui būdingi itin sudėtingi jungtiniai procesai, gamybos srautai, įvairios struktūros, aukšti kokybės reikalavimai ir ilgas statybų ciklas. Dėl vadybos procedūrų, statybos procesų ir perdarymo išeikvojama daugybė betono ir laiko. Be to, gali būti, kad galutinio statinio kokybė patenkins ne visus kliento reikalavimus.

Šiame darbe nagrinėjami praktiniai statybų proceso ir kokybės didinimo sprendimai, naudojant surenkamąsias kompozitines konstrukcijas, pagrįstas „Šešių sigma“ metodu. Analizuojant statybos procesą, ieškant svarbiausių gerintinų veiksnių, kurie leistų patenkinti klientų poreikius, taikytas „Šešių sigma“ D-M-A-I-C modelis. Šiame tyrime nustatoma, kas daro įtaką statybų procesui ir statybų kokybei, o tuomet parenkamos projektavimo ir metodų taisymo priemonės. Tokiu būdu pagerinamas statybų procesas ir padidinama tikimybė, kad kokybė išliks aukšta esant įvairaus lygio veiklos efektyvumui, taip pat siūlomos geriausios maišymo proporcijos. Tokios gerinimo priemonės padeda įveikti ir gerokai sumažinti betono trūkinėjimą ir praslydimą statybose. Remiantis „Šešių sigma“ projektavimo modeliu (apibrėžti, apibūdinti, optimizuoti ir pagrįsti, t. y. DCOV) ir naudojant baigtinių elementų analizės modelį (ANSYS), šiame tyrime sukuriamas kompozitinis plieno ir betono modelis, skirtas moksliniam ir ekonominiam taikymui statybų sektoriuje.

Siūlomą būdą sudaro trys etapai. Remiantis matavimais ir statybos procesų analize, juodąjį „Šešių sigma“ diržą turintiems konsultantams, statybų vadovams, inžinieriams, klientams ir architektams modelis padeda iš anksto pastebėti ir pašalinti kritinius defektus bei triktis.

**Reikšminiai žodžiai:** „Šešios sigma“, statybų kokybė, DFSS, statybų sektorius, procesų tobulinimas.

**Florent Megan TCHIDI.** Research assistant, PhD Candidate at Tianjin University in the Department of Management Sciences and Engineering. He has a Master of Sciences in Structural Engineering. Author and co-author of several scientific papers. Member of ASCE (American society of Civil Engineers), ASME (American Society of Mechanical Engineers) and (IIIS) International Institute of Informatics and Systemics. His main research areas include Steel-Concrete Structures, Prefabricated Structures, Structures Optimization, Six Sigma, Lean Construction, Productivity and Quality Management in construction.

**Zhen HE.** PhD, Professor, Supervisor and Vice Dean of College of Management and Economics of Tianjin University. He is author and co-author of more than 100 scientific and special papers, lecture notes and textbooks. Active member of China Quality Association, he is Black Belt expert. He has carrying out research on, Quality, Productivity and Performance Improvement in the Manufacturing Industry. Research interests: Six Sigma, Quality Management, Industrial Engineering, Statistic process.

**Yan Bo LI.** Assoc. Prof., Supervisor. Dept of Civil Engineering, Tianjin University. He is author and co-author of more than 50 scientific and special papers. Research interests: Structural Stability, Structural Reliability, Steel-Concrete Structures, Seismic Design and Experimental Research.