EMPIRICAL CONSIDERATION OF PREDICTING CHAIN FAILURE MODES IN PRODUCT STRUCTURES DURING DESIGN REVIEW PROCESS

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ABSTRACT

Failure Modes and Effects Analyses (FMEA) have widely been used in design review processes. In the cases of complex systems, failure modes on a top system are resulted from failure chains among component in the system. Predicting method to reveal failure chains is highly depending on practitioner's experiences and no logical guidelines have been established. This paper describes the modified DRBFM (Design Review Based on Failure Modes) to effectively find the latent failure chains. In first step, normal state of functional and structural model is set. Next, by comparing features of the models with the one in past product, failures are specified, After failures are found, interference changes by failures is discussed in order to reveal newly-generated failure chains. To compare the performances of detecting failure chains, 28 mechanical engineering students conducted the conventional FMEA or the modified DRBFM method by themselves. The result significantly showed that the modified DRBFM method is more effective in detecting failure chains which causes the errors of underestimating.

Keywords: DRBFM, FMEA, Product evaluation, Design Reliability Engineering, Safety Engineering

1 INTRODUCTION

Failure Modes and Effects Analyses (FMEA) have widely been used in design review processes in order to prevent failures in service [1]. Designers who make the FMEA datasheet are usually requested plenty of knowledge and experiences about failures modes. Supporting tools, such as logical guidelines or failure records, to effectively make them are then indispensable because veterans are retiring so rapidly. Suzuki pointed out the following difficulties in predicting failure scenarios [2],

1. A procedure for predicting the specific contents of failure scenario is unclear. It highly depends on a designer's knowledge or experiences.
2. It is very difficult to use past failure records in design review processes to proactively predict future failures because the form of the record itself is not suitable .,

Accident record including its faults have been arranged in some fields [1,2]. However, it is only effective in alarming people to take care of the failure, because these records include various terms even in the case of similar types of accident. Finding latent failures in their product by using past accidents is still the responsibility of designers. Yoshimura in TOYOTA motors argued that the connections among elements in products are main problem in considering failures [3].

Before discussing latest approaches, we have to specify two types of failure modes;

1. Functional failures; abnormal states in functional components (*Fig. 1*), e.g., loss output, excessive input etc. These expressions do not include mechanisms of failure.
2. Physical failures; abnormal conditions in structural model (*Fig. 2*), e.g., deformation, rupture, etc. These expressions directly relate to their mechanisms, e.g., when deformations is considered, deformations can be easily connected its mechanism of Hook's law.

It should be noted that physical failures often lead to functional failures. Therefore, in order to prevent functional failures, the process of considering physical failures, not only functional ones, is much important. However, this process is extremely difficult to be completed only based on past accident data because physical failures are often happened by the deviations in their service environment. The specific procedure for predicting failure scenarios is not established yet.

There are various approaches in order to effectively find latent problems in a design stage. Wright [4] reviewed the process of managing engineering changes in a product. He argued that effective process of visualizing the effect flow by the engineering changes through a design process is very important to

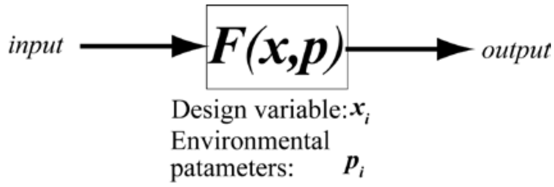

Fig. 1 Functional model (1 input-1 output)

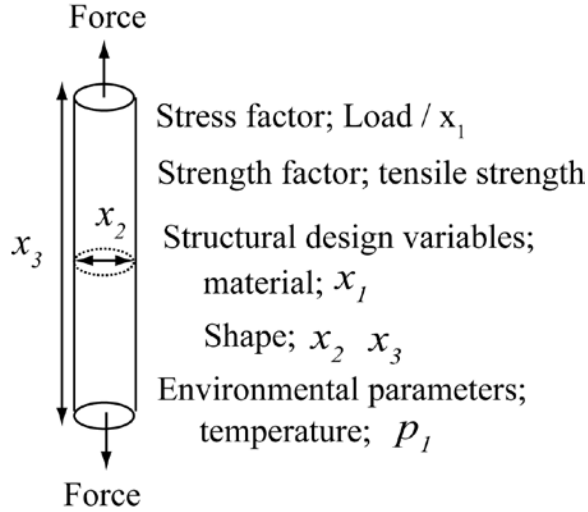

Fig. 2 Structural model

analyze the effect of product's quality. Eckert *et.al.* [5,6] discussed the various methodologies to visualize risks involved in engineering changes; risk matrix, cascade model of effect propagation by changes and component connection network. They pointed out the critical path if risk by the engineering changes should be visualized by using the discussed methods in order to secure the reliability of the considering products. Wirth [7] pointed out the lack of guidelines for practitioners of FMEA. They also suggested the use of input-output functional model to detect functional failures. Deviations in the functional parameters are connected to specific failures, retrieved from failure taxonomy database. Their approach focuses on functional failures, not included physical failures. Tumer and colleagues [8,9,10] also used input-output model to identify functional failures. Hirtz *et.al.* [11] constructed standard function taxonomy. They focused on calculating the probability of system failure and little discussed the process of setting failure scenario. Huang and Jin [12] discussed conceptual stress-strength model to express functional failure. Their approach also showed little in setting the contents of failures. Clarkson *et.al* [13] argued that interferences among element should be considered through FMEA process. Dependency matrix they proposed is beneficial to reveal interferences among element, which highlights potential failure chains. However, in the cases of physical failure, failure chain is not always going along the path of functional interferences. They did not separate functional models and structural models. Physical failures can lead to functional failures. In order to completer FMEA process including the determinations of causes of functional failures, predicting physical failure chains is necessary. However, conventional FMEA process did not distinguish physical failures from functional failures and then should be improved.

This study aims at establishing the process of predicting chain failure modes by using failure modes networks[5] and updating the boundary conditions of structural model of an element interfered by other failures. Section 2 explains the contents of revised DRBFM process that includes the above proposal. Section 3 demonstrates the case study of the revised DRBFM for a motor bicycle. Section 4 shows the experimental result of the performances of the revised DRBFM compared with the conventional FMEA in predicting a failure chain.

2 REVISED DRBFM METHOD

2.1 Stress-Strength model

Stress-Strength model (SSM) is general concept of determining physical failures [1-3]. Failure states in SSM are expressed by the following equation.

$$(\text{Stress factors}) > (\text{Strength factors}) \quad (1)$$

Stress factors show the degree of energy to break structures, such as forces, chemical attacks or electric voltages etc. Strength factors describe the degree of resistance in materials to be broken. When we consider physical deformation, stress is physical stress (force per internal area) and strength is tensile strength (maximum stress at breaking.) Both factors are affected by service environment, e.g., tensile strength is decreased in corrosive media. Consequently, we have to discuss the balance of stress and strength under a certain environment.

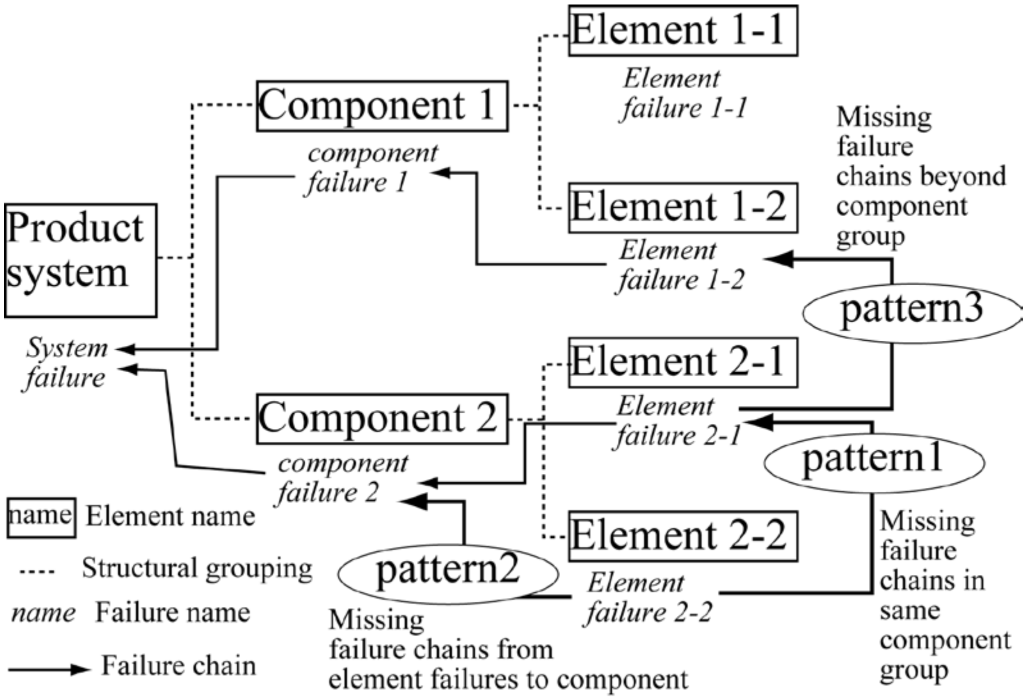

Fig. 3 Three types of failure chains in product structure

2.2 About DRBFM

Shimizu proposed Design Review Based on Failure Modes (DRBFM) in order to support designers to predict failure modes with ease [14]. The DRBFM process contains as the follow steps,

1. Setting past reliable conditions of parts in service
2. Setting design conditions of newly developed parts
3. Determining the changes in design conditions (intentional changes in shapes, materials, manufacturing method etc and environmental changes in service conditions) by comparing both the design condition
4. By using the detected changes (sources of failures) and failure modes list, designers predict failure modes from the changes.
5. Considering the main factor of failure modes by using FTA
6. Thinking countermeasures for the root of main factors.

2.3 Underestimation errors of DRBFM by missing hidden failure chains

Though the DRBFM process is effective in predicting latent failure modes [1], contains three types errors that suffers its performances.

- Unnoticed errors; A problem that designers did not consider. No measures were taken.
- Underestimation errors; A problem that designers noticed but took no measures to prevent it because the designers estimated only partial damage and missed failure chains from a considering failures to entire system failure.
- Misunderstanding; A problem that the designer noticed and took insufficient measures, because of his lack in knowledge or experience.

Unnoticed errors can be reduced by using structural part diagrams [15]. Misunderstanding errors can also be found by setting suitable roles of participants and discussion processes [16]. However, solutions to reduce underestimation errors are not specified because it relate to complex connections among parts in product hierarchical structures. Real accident tends to happen by the complex causes that owe to failure chains. The solutions are then necessary to prevent accidents effectively.

Fig. *3* shows the type should be subdivided as the follows, each of which needs distinct preventive measures.

Pattern 1 Missing failure chains in same component group

Pattern 2 Missing failure chains from element failures to component

Pattern 3 Missing failure chains beyond component group. Links in structural groupings do not always much the failure chains that is resulted from physical connections.

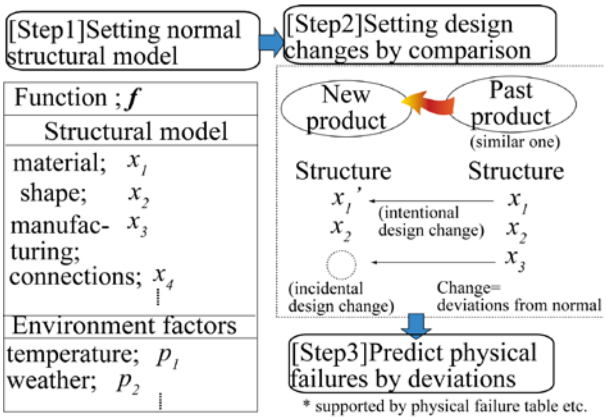

Fig. 4 Procedure of the revised DRBFM method1; Predicting failures in one elements

Table 1 Example of structural dependency matrix

	Component	Element 1-1	Element 1-2	Element 2-1	Element 2-2
Component	Canging point	Yes	No	No	No
Element 1-1	Yes	Failure Mode			
Element 1-2	No	○			
Element 2-1	No	×	×		
Element 2-2	No	○	×	×	

○;Existing interferences; ×;No interferences

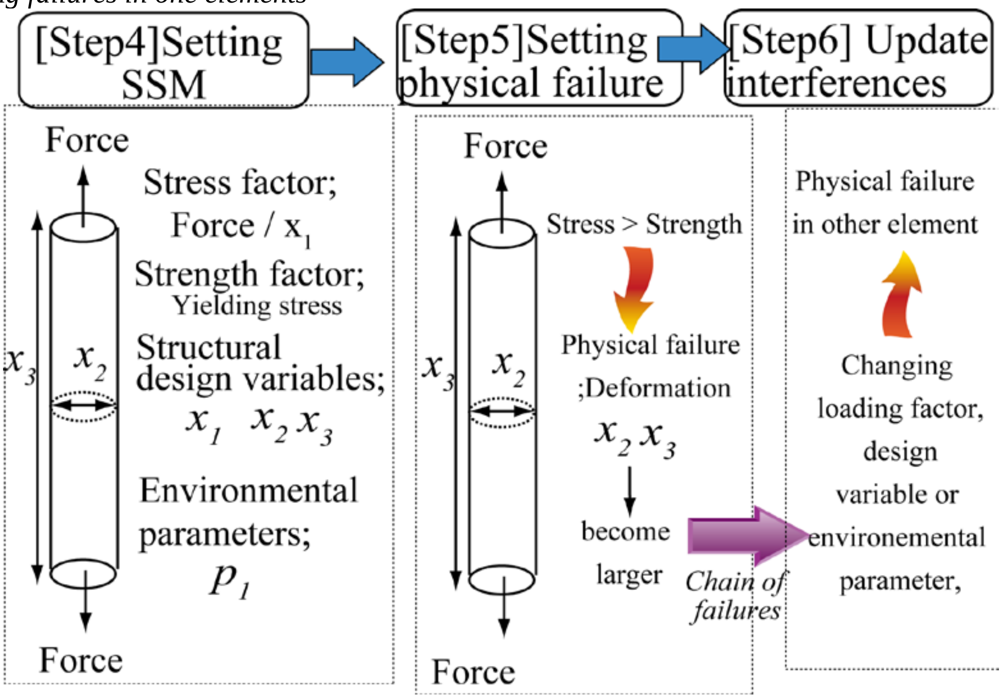

Fig. 5 Procedure of the revised DRBFM method 2; Predicting failures chains

In the cases of considering pattern 1 and pattern 2 errors, failure links normally match the links among structural grouping; the conventional DRBFM process is applicable. However, in the case of considering pattern 3 errors, the failure chain is not along with the structural grouping. In this case, designers have to prevail interferences of failures emerged from the changes of conditions in functional connections among parts, physical contact or environmental situations etc. To specify predicting process of pattern 3 errors, we revised the DRBFM process by combining the concept of failure networks proposed by Eckert [13] and robust modelling process [17] as the follows,

1. Making structural dependency matrices in the same level of product structure, shown in Table 1.
2. Setting failure modes in one element by comparison(Fig. 4)
3. After setting a failure in one part, designers will consider the changes of "normal conditions" of neighbour elements whether new deviations can be emerged. If the new deviation is defined, new interferences between two elements will be drawn in product structure.
4. Designers consider whether the new interferences can affect stress-strength state of others. If the interfered deviations can result in failures of other parts, it becomes failure chain(Fig. 5)

2.4 Procedure of the revised DRBFM method (Figures 4 and 5)

2.2.1 STEP 1 Setting normal model

1. Specifying design conditions (service conditions, normal user's configurations or environmental conditions)
2. Deposing systems into a set of sub-systems, parts and elements
3. Definitions of functions for all the sub-systems, components and elements.

2.2.2 STEP 2 Setting design changes by comparison

1. Selecting base target for comparison which has same function for a considering elements or was the similar element.
2. Comparing design conditions between base target and the considering part in order to specify differences to be named intentional or incidental changes. Intentional changes mean that changes are made by designer's decision and incidental changes mean that changes are resulted from changes in service environment etc.

2.2.3 STEP 3 Predict physical failures by deviations

1. Considering specific failures of an element caused by predicted changes. By combining the predicted failures and functionally abnormal conditions, failure mode is determined.
2. Checking whether all the engineering changes were considered to lead to some failure modes to prevent unnoticed errors.

2.2.4 Setting structural dependency matrices (Table1)

1. Setting existing interferences , such as functionally connections or physical fixing, among elements.
2. Fulfilling the interference conditions among parts in part interference matrices.

2.2.5 STEP 4 Setting stress-strength model of element.

1. Setting loading factor and strength factor of an element.
2. Normal states of structural model is also determined from the result of step 1

2.2.6 STEP 5 Setting physical failures

1. Considering the cases of excessive loading or decreasing of strength.
2. Each cases are connected to specific names of physical failures, normally failure taxonomy is prepared by knowledge data base.

2.2.6 STEP 6 Update interferences to consider failure chains.

(A) Predicting physical failures corresponding to Pattern 2 error

1. Considering the stress-strength model of a component including excessive loading factors or weakened strength factors.
2. Checking the contents of physical failures of interconnected part.
3. Checking whether the physical failure of the interconnected element can affect excessive loading factors or weakened strength factors, which can generate new deviations.
4. Failure mode of the components from the failure chains is named by the combination of the newly detected physical failure and functional failures.

(B) Predicting physical failures corresponding to Pattern 3 error

1. Considering the stress-strength model of a component, including excessive loading factors or weakened strength factors.

1. Checking the contents of failure modes of interconnected element.
2. Checking whether physical failures of the interconnected element can change the normal conditions of the neighbour element. If changes. The new interferences are drawn in Table 1.
3. Determining new physical failures by new deviations generated by failure chains.

After all processes are completed, result is filled in DRBFM worksheet.

3 CASE STUDY OF THE REVISED DRBFM METHOD

3.1 Procedure of the case study

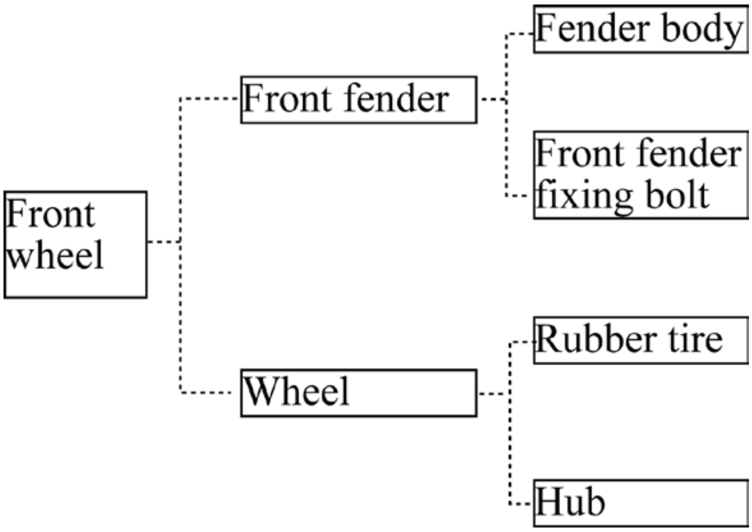

Fig. 6 Product structure of target A (base) and target b (comparing)

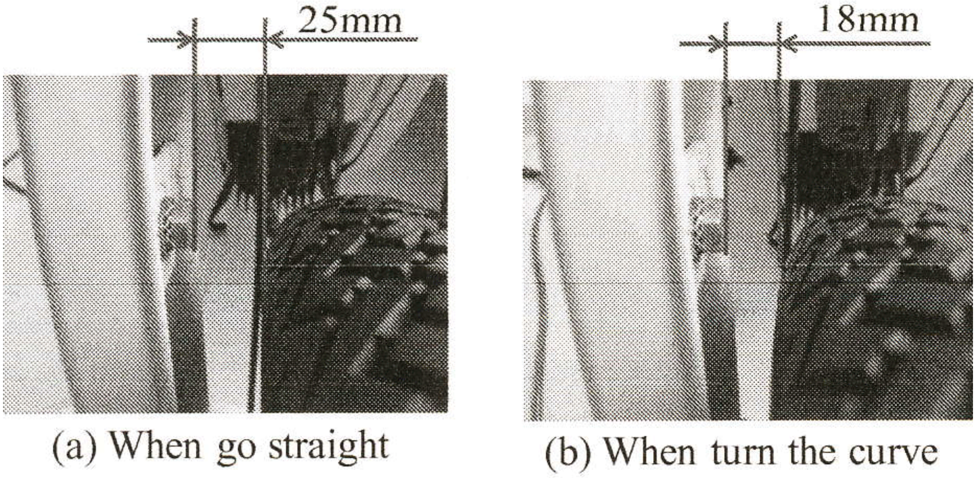

Fig. 7 Normal conditions Target A; no interferences found between front fender fixing bolt(left) with rubber tire(right)

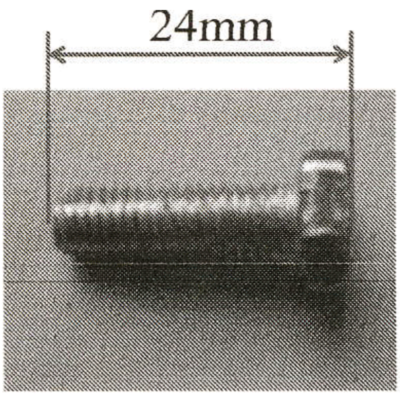

Fig. 8View of Front Fender's Fix Bolt. If bolt is completely loosened, it cannot contact tire,

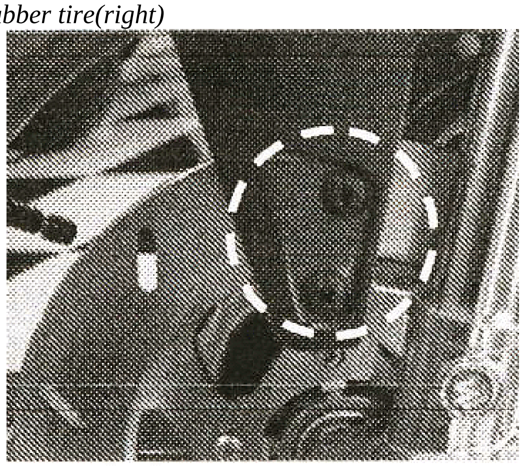

Fig. 9 Structure of fender (right) and rubber tire(center) in target B. bolt head is embedded and has no possibility of protrusions

We chose the parts of front wheel of two types of motorbikes. *Fig. 6* shows the product structure of Target A and Target B.

3.1.1 STEP 1 Setting normal model

Table 2 Normal states of functions and structural model.

		Target A(base)	Target B (comparison)
Function model	Function of front wheel	Running on roads	
Structural model	Number of riders	One	one
	Normal loading (Rider’s weight + goods)	Max 80 +15 kg	Max 80 +30 kg
Environmental factors	Weather	Sunny Cloudy , Rainy	
	Road conditoins	asphalt-paved	

Table 3 Finding deviations (incidental changes) by comparing detailed structure of both targets.

Component	Target A(base)	Target B (comparison)
Front fender	Front Fender’s Fix Bolt exist between fender body and rubber tire	No protrusions are found.

Table 2 shows the normal states of functions and structural model. There are little differences in both states. Figure 7 and 8 shows the detailed normal states of element. These figures reveal no interferences between them is existed.

3.1.2 STEP 2 Setting design changes by comparison, STEP 3 Predict physical failures by deviations
Table 3 shows the differences of the structures between target A and target B. Figure Fix bolt of front fender locates the side near a tire in the case of target A as shown in Fig. 7(a). There is no such a bolt in the inside of the front fender of target B as shown in Fig. 9.

Table 4 shows the example of DRBFM worksheet for rubber tire’s main body. In this case, a normal condition is an equivalent condition between the value of load from grounds and internal pressures. An abnormal condition is a hole on the body which leads to the loss of internal pressures to result in functional loss condition of the rubber body. Failure mode is name by “Impossible to absorb shocks or load from ground by the hole on the body”.

3.1.3 Definition of interferences
In the normal condition, there is no physical contact observed among tire, fix bolt of front fender and a hub. However, Fig.7(b) shows the narrowed space between tire and the head of fix bolt when the front wheel is inclined in curving, which emerges the concern of friction (types of interferences)

3.1.4 STEP 4 Setting SSM to STEP 6 considering the failure chains
As shown in Figure 7, space between the tire and the fix bolt is 25mm in the normal condition (a) and 18mm in the inclined conditions (b).Fig. 10 shows the entire shape of the fix bolt of front fender whose total length is 24mm. That means in the normal conditions no physical contact are occurred between the tire and the fix bolt, as shown in Fig. 10(b).

Next, the fix bolt, is considered including its failure conditions. Fig. 10(b) shows its process visually. When considering the inclined condition of the hub (in curving or failure condition), inclined angle increases compared with that in normal condition. In addition, typical failure modes, loosening of bolt are easily predicted that narrows the distances to tire from the head of bolt. By combining these failures, new interferences, frictions on the tire surface by the head of the fix bolt is then predicted. This is new physical failures by new interferences. This failure is called “failure A” in latter sections.

3.1.5 Drawing failure chains
Fig. 11 shows the summary of failure influences. The failure A is emerged by the interferences beyond the different structural groups. Failing to predict the failure A is corresponding to the pattern3 errors of underestimations.

Table 4 Example DRBFM work sheet for failure chains at one component-element structure

Element	Function	Failure Mode	Mechanism	Cause	Solution: In design	Solution: In evaluation	Solution: In production	Attention
Rubber Tire's Main Body	The tire absorbs a shock and grounds	The hole opening ↓ Impossible to absorb	Wear	Front Fender's Fix Bolt loosening + Hub tilting in turn ↓ The bolt contacting and friction is generated	To do durability test and deciding period of use		Covers the bolt to prevent loosening	Please check user's manual

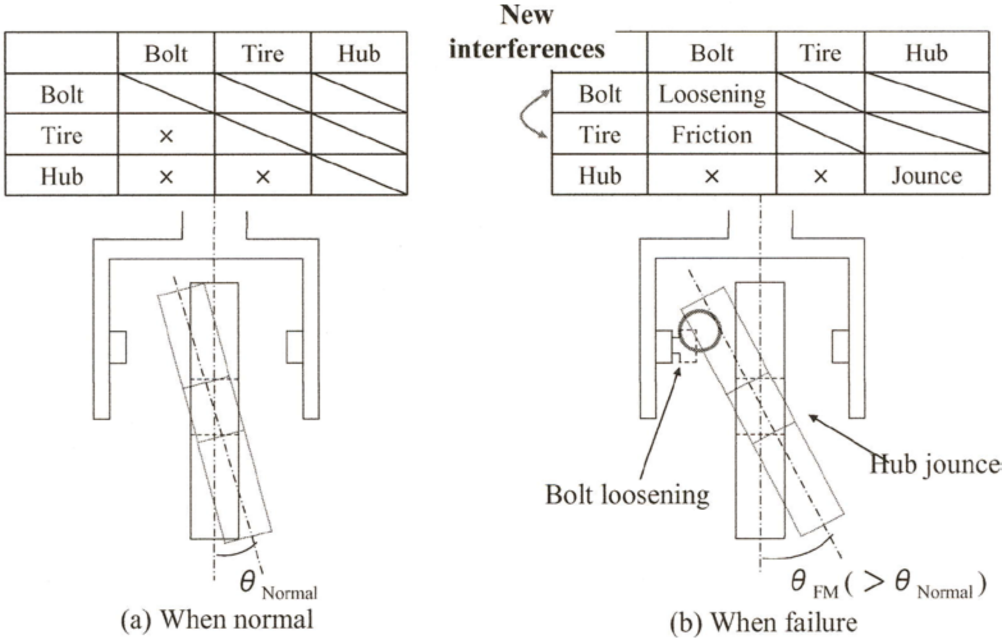

Fig. 10 Illustrated process of determining failure A by newly-generated failure chain

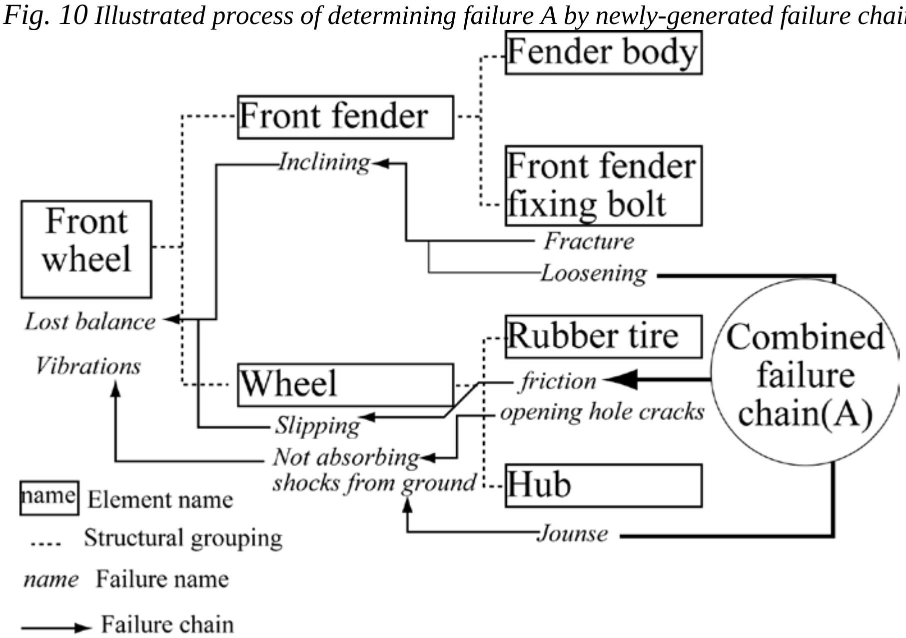

Fig. 11 Failure chains including failure A, generated by combined failure chains

4 EXPERIMENT FOR THE PEFORMANCE OF THE REVISED DRBFM METHOD IN FINDING FAILURE CHAINS

4.1 Subject and the detailed process of practicing.

We collected 28 mechanical engineering students. They were divided in to two groups; FEMA group and revised DRBFM group. The gender and the age of each group are shown in table 5.

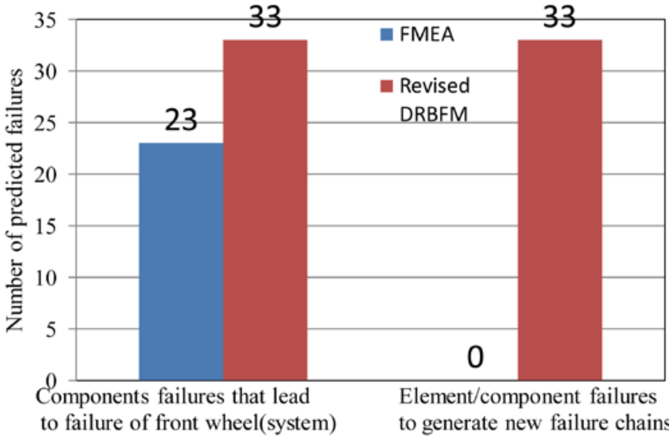

Fig. 12 Results of predicting failure chains

Table 5 Face sheet of participated students

Group	The number of people	Sex		Average age
		Man	Woman	
FMEA	14	14	0	21.6
DRBFM	14	14	0	21.2

Table6 Statistical analysis result of the ratio of persons who could find failure A

Group	Ratio of persons who could find hidden failure chain A
FMEA	4/14 =0.286
Revised DRBFM	11/14=0.786

T-statistics for t-test ; T=2.65 (significance level p=0.004)

Table7 Statistical analysis result of the number of predicted failure chains by both methods

Group	Participant	Mean	Standard deviation	MAX	MIN
FMEA	14	1.36	0.71	3	0
Revised DRBFM	14	2.57	2.26	6	0

T -Statistic for Welch's test ; $T_{20.6}$ = 2.64 (significance level p=0.008)

The authors gave all the students following document to conduct either method by him/her self.

- Practice guide of the conventional FMEA method or the revised DRBFM method.
- Failure influence flowchart (only part names are written)
- Pictures for both targets (Figs 6 to 9)
- Agreement document for academically use of their results

Target of analysis is limited the front wheel structure shown in Fig. 6. The structure has two parts; Front fender (elements; front fender body, front fender fix bolt) and Wheel (element; rubber tire, hub). The student is requested to predict as many as failure modes they could by using either method. All the data sent to the students by e-mail and answers are also sent by e-mail up to 2weeks. To emphasize the student's motivation, rewards according to the top-3 obtained number of failure modes were prepared to the students. They are told these awards before practicing. Time of practice is not limited because rewards are not increased by increase of thinking time.

4.2 Statistical analyses

Each result was checked by the authors to determine unique failure mode to accurately count its number. Failure modes that place on the root of failure chains to another parts or higher components were also counted. Subsequently, the difference of the ratio of finding failure A in each group and the difference of the average number of the failure modes to lead another failure modes in each group were statistically analysed by using t-test and Welch's test[18].

Table 6 and 7 show the result of finding ratio and the number of inducement failure mode. Both difference are significant at p=0.05. Therefore, the revised DRBFM can effectively support users to predict complicated failure chains more than using the conventional FMEA. This result demonstrates the use of the revised DRBFM method can improve the quality of design review by reducing the error of underestimation.

4.3 About the performances of preventing the errors of underestimations.

Figure 12 shows the predicted result of failure modes by using conventional FMEA method or the revised DRBFM method by same person. Using the revised DRBFM method enabled the user to predict more failure chains. During the revised DRBFM procedure, some deviations from previous reliable conditions are emphasized by comparisons to help users to focus the changed point as the candidates of concerns for failure modes [3]. In addition, introducing the considering process of failure chains combined by normal functional conditions, deviations from the normal conditions and updating interferences by the deviations can support users to see explicitly an complicated failure chains such as Failure A in Fig.11. Missing such failure chains leads to the error of underestimation and then the revised DRBFM is effective in reducing the error of underestimation by providing users to chase failure chains with clearer and easier logic.

5 CONCLUSIONS

The revised DRBFM method is arranged in order to reduce the error of underestimation which is yielded by failing the complicated brunches of failure chains. Users of the revised DRBFM method could significantly find more failures which lead to other failures. The revised DRBFM can effectively support users to predict complicated failure chains more than using the conventional FMEA. This result demonstrates the use of the revised DRBFM method can improve the quality of design review by reducing the error of underestimation.

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