Int J Syst Assur Eng Manag (Oct-Dec 2011) 2(4):319–324
DOI 10.1007/s13198-012-0081-1

ORIGINAL ARTICLE

Taguchi methods and finite element methods in reliability based crashworthiness and risk analysis of motorcycle frame

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Received: 20 November 2011 / Published online: 25 January 2012

Abstract Safety measures in vehicles have been given prime importance by manufacturers and customers. In terms of sales, the market share of motorcycle is very high amongst different types of automobiles. Deaths due to accidents involving motorcycle is also high compared to other vehicles. Considering the impact of improving the crashworthiness of motorcycle frames on safety of the riders, this paper addresses crashworthiness of motorcycle frame under frontal impact force. Modeling and analysis of the motorcycle frame is performed using ANSYS LS-DYNA whereas optimization of simulation results was carried out using Taguchi methods. The diameter and thickness of front members of the frame and material of the frame are considered as random variables. The response variables studied are mass of the frame, deformation at the front end and frame reliability. The reliability of the frame is evaluated with respect to limit state of deformation. The outcome of this study is the designs of the frame which satisfy mass, deformation and reliability criteria. With the optimal combination of variable obtained from optimization study, risk analysis is carried out on the frame in order to understand the relation between deformation and cost of exceeding deformation in monetary terms.

Keywords Crashworthiness · Reliability · Taguchi methods · Finite element methods · Motorcycle frame · Deformation · Risk analysis

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1 Introduction

A lot of research has been carried out on cars on safety issues. The need for a study on safety issue in motorcycles is due to the two important reasons: a large section of population travel on motorcycles and the percentage of motorcycles among the vehicles meeting with accident is high. The Society of Indian Automobile Manufacturers (SIAM) indicated that market share of two wheelers on the basis of sales is 76%. Figure 1 shows the domestic sales trend in India for 2004–2005 to 2010–2011. National Crime Records Bureau, Ministry of Home Affairs, Government of India, published their report titled Accidental Deaths & Suicides In India (ADSI-2010) which revealed that accidental deaths due to two wheelers is highest among all vehicles with 21% share in the year 2010. Figure 2 reports the percentage of vehicles meeting with accident for last 6 years.

The authors of this paper attempt to study the behavior of the motorcycle frame under impact load. The optimization of motorcycle frame involves minimizing mass of the frame to make it light weight, minimizing deformation due to impact and maximizing reliability. In order to study the crashworthiness behavior of the frame, diameter, thickness and material of the frame members are considered as design variables. The response variable of interest are mass of the frame, deformation at front end and frame reliability.

2 Crashworthiness

Literature review on crashworthiness revealed various means of its analysis and optimization. Kurtaran et al.

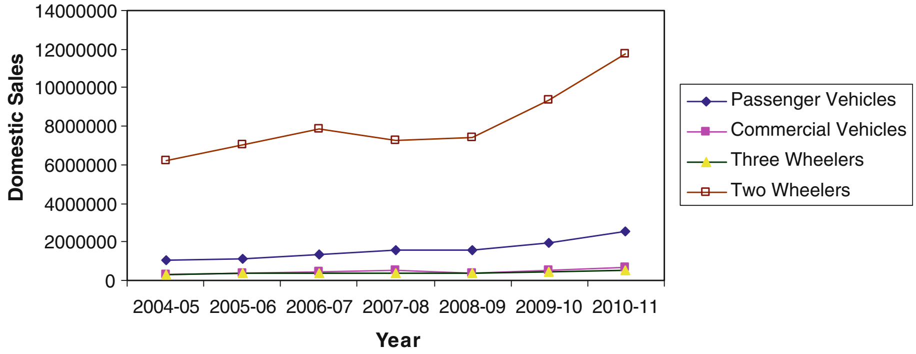

Fig. 1 Domestic sales trend of vehicles (*Source* SIAM)

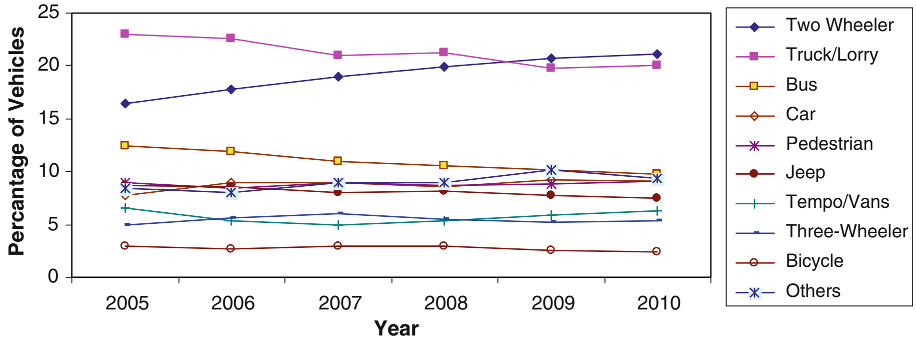

Fig. 2 Deaths on road vehicle-wise (*Source* ADSI)

(2002) has used three different models of crashworthiness for applications relating to optimization of cylindrical tube, studying vehicle impact with rigid pole and optimization of concrete barrier shape. Maximum energy absorption is used as a model for the optimization of cylindrical tube subjected to impact force. For optimizing vehicle impact with a rigid pole maximum acceleration is used as a model for crashworthiness. In case of optimization of concrete barrier shape, the crashworthiness model used is rotational displacement of the vehicle. In optimization of corrugated tubular structure, tapered tubular structure, tapered components with rectangular cross-section and tapered components with circular cross-section, ratio between the maximum and minimum crushing force is used as objective function (Avalle et al. 2002). Study of collision of three car train with three different vehicles has been presented by Dias and Pereira (2004) with deformations, forces and accelerations as design functions. Dimensions of aluminium tubes were optimized using maximization of absorbed energy and specific absorbed energy as objective functions when the tubes were subjected to impact (Zarei and Kroger 2006). Since the behaviour of the system is uncertain in real life, stochastic studies are very much important in crashworthiness analysis. Such stochastic studies have widely been attempted on cars to improve occupant safety and comply with the statutory safety guidelines. Reliability based design optimization using performance measure approach and hybrid mean value was attempted on a large scale vehicle side impact to study crashworthiness (Youn et al. 2004). Sinha (2007) has presented a probabilistic methodology which is applied on vehicle crashworthiness design optimization for side impact with objective functions like structural weight and front door velocity under impact. They used approximate moment approach and reliability index approach for computation of safety reliability index. Response surface methods and Monte Carlo Simulation were used for optimizing front rail structure and vehicle structure subjected to frontal impact Redhe et al. 2009. Reliability based design optimization was performed on an automotive to analyze crashworthiness and to study the effect of reliability allocation in different failure modes by Acar and Solanki (2009). Abbasi et al. 2011 presented crashworthiness improvement using Taguchi parametric design and obtained 14% improvement in performance criteria over baseline design. Developments in finite element methods have increased the simulation capabilities of crashworthiness studies to great extent. Bulik et al. 2004 presented use of M-Xplore extension of the Radioss software in crash simulation. Comparison of the crashworthiness of various bottom and side structures using LSDYNA was carried out by Naar et al. (2002). A limited literature is available on crashworthiness studies on motorcycle frames. Tan et al. (2006, 2009) conducted an experimental study of deformation behaviour of motorcycle front wheel-tyre assembly under frontal impact loading using energy absorbed by the assembly as crashworthiness measure.

EEVC (1993) report revealed that 87.6% of impact on the motorcycle is on the front side. Reliability analysis of motorcycle frame is not reported widely and hence the authors have made an attempt in this work to study crashworthiness of motorcycle frame taking reliability into account. In this work deformation at intersections of members at the front end is used for crashworthiness analysis under frontal impact load.

3 Taguchi methods

Taguchi methods have been widely used in optimization of process parameters in manufacturing industry. Their application has also been extended to design and other non-manufacturing areas. Genichi Taguchi introduced this efficient and effective optimization method way back in 1900. Various applications on Taguchi methods are explained by Phadke (1989) and Ross (1996). A preliminary study of the frame using finite element software ANSYS LS-DYNA revealed that the frontal members 1 and 2 shown in Fig. 3 are affected due to impact and hence these were considered as the variables of interest for optimizing the motorcycle frame. The other variable of interest is material of the frame. Table 1 shows the variables and their levels. The levels were chosen after studying eight different models of four reputed manufacturers. Even though, the looks of the motorcycle depends on its topology, the dimensions of the various motorcycles vary as per manufacturers specifications. The material considered for analysis are ASTM A500 steel grade C (Marks and Baumeister 1987; Davis 1994) and Aluminum 7003 (Joseph and Ueda 2001). Table 2 shows the mechanical properties of the material. Since there are five factors to be studied at two levels each, L8 orthogonal array shown in Table 3 is used in this study.

Experiments were conducted using simulation on finite element software ANSYS LS-DYNA, using the factor levels shown in Table 3. A load of 6,000 N was applied on the frame. Except members 1 and 2 of the frame, the diameter and thickness of other frame members are fixed at 22 and 2.0 mm, respectively. The responses recorded and analyzed are mass, deformation and reliability of the frame.

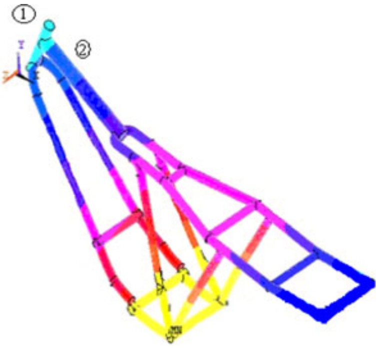

Fig. 3 Motorcycle frame model

Table 1 Variable and their levels

Variable	Variable description	Levels	
		1	2
A	Diameter of member 1	40	50
B	Thickness of member 1	1.5	2.5
C	Diameter of member 2	30	40
D	Thickness of member 2	1.2	2.0
E	Material of frame	Aluminium	Steel

Table 2 Mechanical properties of steel and aluminium

S. no.	Material	Young's modulus (GPa)	Density (g/cm^3)	Poisson's ratio
1	Aluminium 7003	70	2.78	0.30
2	Steel	200	7.85	0.30

Table 3 Taguchi L8 OA

Trial no.	A	B	C	D	E
1	1	1	1	1	1
2	1	1	1	2	2
3	1	2	2	1	1
4	1	2	2	2	2
5	2	1	2	1	2
6	2	1	2	2	1
7	2	2	1	1	2
8	2	2	1	2	1

Deformation of the frame at the intersection of member 1 and member 2 was recorded from the FEA simulation runs.. Eqs. 1 and 2 are used for computing mass of the frame for two different types of material viz. steel and aluminium.

$$Mass_{Steel} = 1171.42(2d_1t_1 - t_1^2) + 1787.95(2d_2t_2 - t_2^2) + 1.41 \tag{1}$$

$$Mass_{Al} = 414.85(2d_1t_1 - t_1^2) + 633.19(2d_2t_2 - t_2^2) + 0.49 \tag{2}$$

where d_1 and t_1 represents diameter and thickness of the frame member 1 and d_2 and t_2 represents diameter and thickness of the frame member 2.

Presence of uncertainty in the system affects performance and safety among other tings. These uncertainties are addressed in reliability studies (Kapur and Lamberson 1977;

O'Connor 2002). Reliability of the frame was computed using a deformation limit criterion which is given by Eq. 3.

$$R = P(\delta \leq \delta_{All}) \tag{3}$$

considering maximum allowable deformation δ_{All}, the reliability expression is shown to be

$$R = 1 - \Phi\left(-\frac{\mu_{\delta_{All}} - \mu_{\delta}}{\sqrt{\sigma^2_{\delta_{All}} + \sigma^2_{\delta}}}\right) \tag{4}$$

allowable deformation δ_{All} is assumed to follow normal distribution with mean of 2.5 mm and standard deviation of 0.15 mm. $\delta$is the deformation observed in the FE analysis.

Taguchi has suggested use of statistical tool called analysis of variance (ANOVA) to determine the significant factors affecting responses. Tables 4, 5, and 6 shows the ANOVA table for responses in the present case like mass, deformation and reliability. The significant factors are determined by comparing tabulated values of the *F* statistic with values from standard statistical tables. With regard to mass, thickness of member 1 is significant at 90% confidence

Table 4 ANOVA on mass

Source	SS	DOF	MS	F
A: diameter of member 1	0.000	1	0.000	0.001
B: thickness of member 1	0.011	1	0.011	5.309
C: diameter of member 2	0.002	1	0.002	0.950
D: thickness of member 2	0.005	1	0.005	2.459
E: material	2.733	1	2.733	1367.705
Error	0.004	2	0.002	
Total	2.754	7		

Table 5 ANOVA on deformation

Source	SS	DOF	MS	F
A: diameter of member 1	0.440	1	0.440	0.511
B: thickness of member 1	1.860	1	1.860	2.159
C: diameter of member 2	1.083	1	1.083	1.257
D: thickness of member 2	0.023	1	0.023	0.027
E: material	2.836	1	2.836	3.292
Error	1.723	2	0.861	
Total	7.964	7		

Table 6 ANOVA on reliability

Source	SS	DOF	MS	F
A: diameter of member 1	0.05	1	0.05	0.40
B: thickness of member 1	0.22	1	0.22	111.86
C: diameter of member 2	0.06	1	0.06	32.08
D: thickness of member 2	0.06	1	0.06	30.59
E: material	0.88	1	0.88	437.94
Error	0.26	2	0.13	
Total	1.54	7		

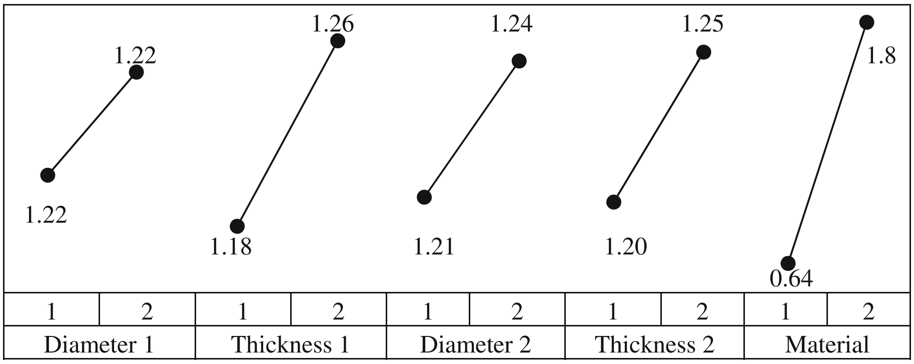

Fig. 4 Response graph on mass

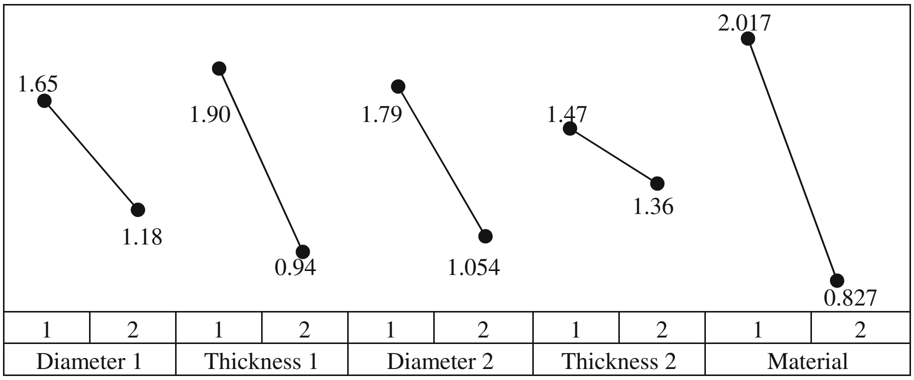

Fig. 5 Response graph on deformation

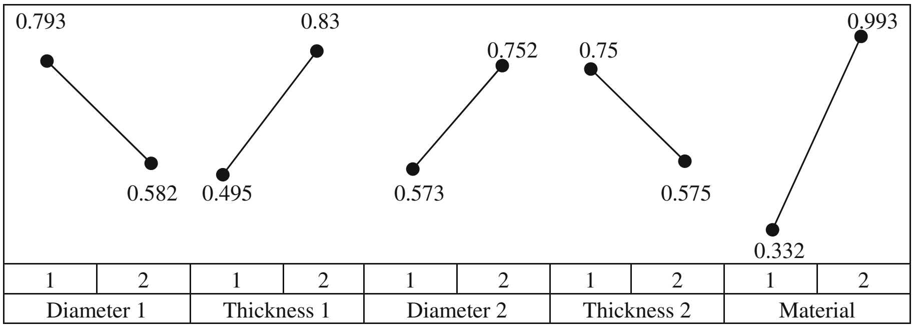

Fig. 6 Response graph on reliability

Table 7 Optimal combination of levels

Response	Variables				
	Member 1 Diameter (mm)	Member 1 Thickness (mm)	Member 2 Diameter (mm)	Member 2 Thickness (mm)	Material
Mass	40	1.5	30	1.2	Aluminium
Deformation	50	2.5	40	2.0	Steel
Reliability	40	2.5	40	1.2	Steel

level, thickness of member 2 at 81% confidence level and material of frame is significant at 99% confidence level. Dimensions of other members are not significant in affecting mass. ANOVA on deformation revealed that thickness of member 1 is significant at 81% confidence level and material of frame is significant at 87% level. Thickness of member 1, diameter of member 2, thickness of member 2 and material of frame is significant at 99% confidence level in controlling reliability of frame. Response graphs were plotted for each of the response: mass, deformation and reliability. Figures 4, 5 and 6 shows the respective response graphs which were used to find optimal levels. Table 7 shows the optimal levels for each of the response variables. Since the objective functions are conflicting in nature, a trade-off may be obtained in deciding which factor combination can be used depending on the required response criteria.

Reliability of the frame was analyzed further to identify the reliability levels for various combinations of dimensions of the frame. Figure 7 shows the curve for reliability versus deformation. It shows that in order to achieve reliability of more than 98%, deformation at the front end should be less than 2.18 mm. Deformation of less than 2.23 mm will give reliability of more than 0.95%. Deformation of 2.25–2.35 mm will yield reliability of 81–95%. Such knowledge about relation between reliability and dimensions will help in determining dimensions based on required reliability levels.

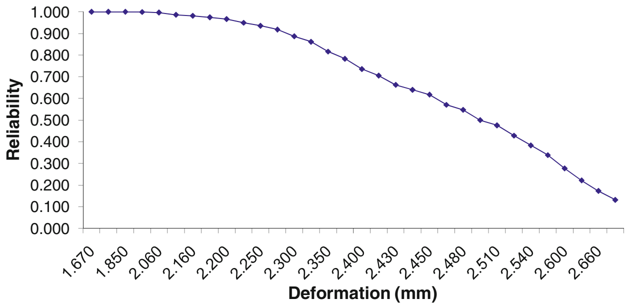

Fig. 7 Reliability analysis based on deformation

4 Risk analysis

Subsequent to reliability studies of the frame, safety of the occupants can be addressed by analyzing the risk in the crash scenario. A relation between deformation of the frame and its effect on the rider can be established. The FEA simulation with increasing impact force can reveal the deformation behaviour of each frame member. Risk analysis comprises of three steps (Modarres et al. 1999):

1. Selection of scenario for analysis.
2. Estimation of likelihood of events, P_i and
3. Estimation of consequences of these events, C_i.

Expected risk value R is given by

$$R = \sum_i P_i \times C_i \tag{5}$$

Monte Carlo simulation was used to estimate likelihood of deformation taking different values, whereas consequence of death of member is considered in terms of monetary loss to the family as reported in Arya et al. (2005), Gururaj (2005). Figure 8 shows the plot of risk versus deformation. For the initial points risk is low because of less deformation. As the deformation increases, risk increases till a certain point. Then it drops due to the less likelihood chances of deformation crossing this limit. The expected

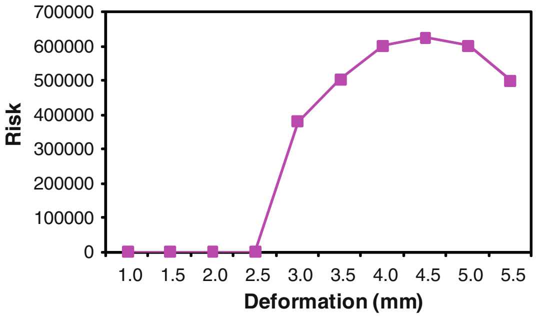

Fig. 8 Risk analysis for varying deformation

risk is very high for deformation of 4 mm onwards. This quantifies the loss to the occupant incase of very high deformation during accident. The frame should have such a dimension which will not give high risk.

5 Conclusions

Deformation of the motorcycle frame under impact force was studied in order to analyze its crashworthiness behavior. While studying crashworthiness, deformation at the front end at the intersection of the members of the frame was considered. Simultaneously mass of the frame was also optimized. Reliability of the frame was evaluated using deformation as a limit state function. In order to reduce the number of experimental runs, Taguchi Method was used for optimization. Statistical tool, ANOVA revealed the important factors for each of the response like mass, deformation and reliability. The optimal levels for the respective response were found using response graphs. Different dimensions of the frame were obtained for various reliability levels. The frame was analyzed for risk and quantified for economical loss to the customer in the event of crash.

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