Study of Drop Test Parameters Using Design of Experiments

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Abstract

Various products such as refrigerators, mobile phones, televisions, washing machines, remote controls, telecommunication and military equipment, etc. are subjected to drop tests to assess their fragility and impact tolerance. It is difficult and expensive to understand the effect of various parameters that affect product performance during the test. Finite element simulations using LS-DYNA® effectively help to understand the effect of these parameters. However, as the number of iterations required can be large, design of experiments approach is used in combination with finite element simulation to extract suitable information. Moreover, it is observed that most of the parameters are common across drop test simulations of different products. The purpose of this paper is to perform a study of parameters that affect the product performance in drop test using LS-DYNA. This study describes the effect of packaging material stiffness, component stiffness and its mass distribution on the time and magnitude of the stress induced in a component, internal energy absorbed by the packaging material and combined relationships between these parameters. The inferences from this design of experiments study will help to understand and predict the behavior of drop test simulations. In addition, these can be applied to all similar drop test applications of various products which will reduce the number of iterations required for design optimization.

Keywords: Drop Test; Design Of Experiments (DOE); Design Optimization; Computer Aided Engineering (CAE); LS-DYNA

Introduction

In this ever developing and competing world, it is important for the companies to launch a new product, which is first time right. Therefore, testing of the product according to practical situations is an important part in product development. Some of these situations involve rigors that might occur during manual or mechanical handling. Drop testing is used to assess the design by measuring the fragility, impact-tolerance of the products and the ability of the packaging to protect the product by understanding the capability of the cushioning materials being used, subject to such extreme cases.

Drop test is performed on various products such as refrigerators, mobile phones, washing machines, remote controls, telecommunication and military equipment, etc. Performing physical drop test of a component will require lot of resources and time which may not be feasible economically. The use of Computer Aided Engineering (CAE) helps in saving these resources and time. It provides us with full spectrum of data i.e. stress, energy absorbed, etc. which is difficult to extract in physical testing. Hailoua Blanco D. [1], Mulkoglu O. [2] and Neumayer D. [3] have discussed about drop test simulation and methodology.

For development and optimization of the product, it is necessary to understand the effect of various parameters on its performance. This can be done by performing tests by varying one variable at a time and under-standing its effect on the output. Although, CAE simulations provide good solution, the number of iterations to be performed to reach an optimum design may be large. Design of Experiments (DOE) helps us to perform a systematic study and find correlations between more than one variable at a time and studying their effects on product performance. Hence, a combination of DOE and CAE can be effectively used for design exploration studies.

Study

Purpose

The purpose of this paper is to describe a study in which DOE of drop test simulation is performed. The effects of variation in input parameters called variables on the performance parameters called responses are studied and inferences are drawn from it. Finite Element (FE) analysis is used to perform the simulations.

Procedure

The procedure followed for this study is shown in Figure 1.

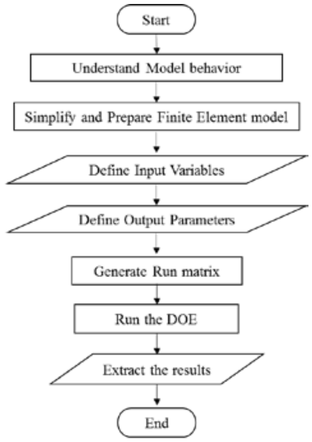


Fig. 1. Procedure for DOE study

The initial step is to understand the model behavior to get an insight of the parameters that are to be considered for the study. Then a simplified finite element model is prepared. The input variables and output parameters are defined and a suitable run matrix is generated for the DOE study. Then the simulations are performed as per the run matrix and the results are extracted from the study. It is to be understood that number of simulations required will increase with an increase in the number of input variables.

Understanding model behavior during drop test

Drop test is carried out to check improper handling during transportation. Usually the component is covered with packaging foam. Also, use of packaging material in the study will help to understand the effect of all variables in wider spectrum.

A typical energy plot for drop test of any component is as shown in Figure 2.

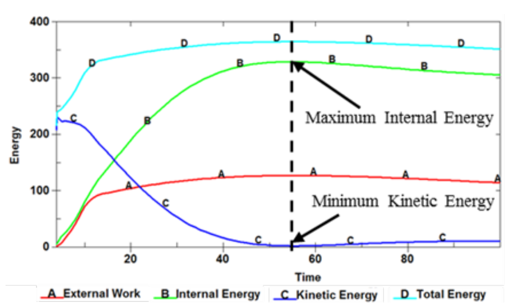


Fig. 2. Typical energy plot for drop test

The product or component is dropped from a certain height on a surface. Thus, the potential energy is converted into Kinetic Energy (KE) during drop. This kinetic energy will start reducing as it comes in contact with the surface and will be converted into work and internal energy. Thus, with reduction in kinetic energy, there will be an increase in external work and internal energy. At certain time, this kinetic energy will reach zero and rebound of component will start. Also, internal energy and work will be maximum at this point. Hence the stress in the component will be at its peak. Therefore, all the results of drop test are to be noted at this particular time. This time is called as rebound start time (t).

Simplify and prepare the FE model

To study the effect of various parameters, it is helpful to simplify the FE model to get the specific set of input variables. For this study, the foam is assumed to be divided into four regions namely Front LH, Front RH, Rear LH and Rear RH as shown in Figure 3. Each region of the foam is assumed and modeled to behave like a linear spring having some stiffness and located at the center of gravity of that particular region.

The FE model of the component along with the foam is prepared and is dropped on a rigid surface from a predetermined height in LS-DYNA [4]. To save solver run time, the component is positioned such that it is just above the rigid surface and corresponding initial velocity is applied at start using *INITIAL_VELOCITY_GENERATION card. Sheet metal and plastic parts are modelled with quad4 and tria3 shell elements, whereas, solid parts like foam are modelled with tetrahedron elements. Contact between the parts and foam is defined by *AUTOMATIC_SINGLE_SURFACE. *AUTOMATIC_GENERAL_INTERIOR contact is used for self-contact of foam. *LOAD_BODY card is used for application of gravity.

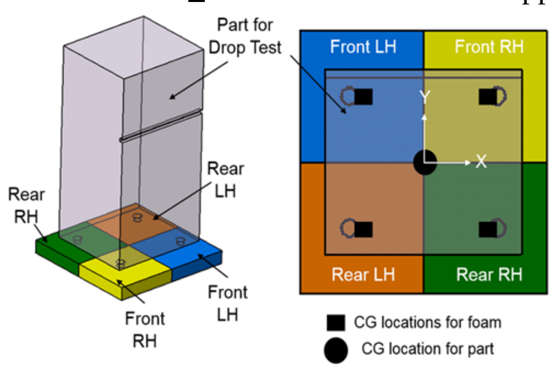


Fig. 3. Simplified model

Define Input Variables

Input variables are the parameters which are varied to study their effect on the output. The choice of input variables depends on the area of interest. The input variables defined for this DOE study are as follows:

- **Component Stiffness (K_c):** Component stiffness is selected as a variable to understand the effect of component's strength on the stresses induced in it. Three values viz. low, medium and high are used.
- **Center of Gravity of the component (CG):** It is the CG of the part or component on which drop test is performed excluding the packaging material. It can be at the center or offset from the center of the part. These two conditions require the study of effect of offset mass on output parameters. The effect of offset CG will be same in any of the direction in the same plane. Thus, all directions need not to be considered separately in this study. Also, during the drop test of a part along certain edge or point will have a similar effect as offset CG. For this study, the CG is considered to be offset towards rear. The effect of variation in CG in Z direction is not considered.
- **Foam Stiffness:** The foam is divided into four parts as discussed. However, to reduce the number of variables and to take advantage of model symmetry, the stiffness of left and right springs at front and rear

end are combined into single entity and are considered as front spring stiffness (K_f) and rear spring stiffness (K_r) respectively. The values of K_f and K_r are taken as low, medium and high for this DOE study.

The drop height may vary for different products, but, for a particular study it will remain constant. Thus, it is not considered as an input variable. Thus, the input variables are K_c, CG, K_f and K_r.

Define Output Parameters

Output parameters are the responses to the changes in input variables. These parameters drive the design and development of a component. The output parameters which are focused upon in this DOE study are as follows:

- **Stress (σ):** The stress is an important parameter to decide the failure of the component. Usually lower values of stress are desirable. Von Mises stress is considered in the study.
- **Internal Energy absorbed (*IE*):** This is the total energy absorbed by the packaging foam during the test. This energy has two components, Internal energy absorbed by front spring (IE_f) and Internal energy absorbed by rear spring (IE_r). However, total energy absorbed (*IE*) has more importance than the individual components.
- **Rebound Start Time (*t*):** This is the time at which rebound starts. At this time, the internal energy absorbed is maximum and the kinetic energy of the component is minimum. All the output parameters are studied at this point, as the stress induced at this time is maximum.

Thus, the output parameters are σ, *IE*, IE_f, IE_r and *t*.

Generate run matrix

The number of iterations for full factorial design can be calculated from equation 1,

$$\text{Number of iterations} = L^n \qquad (1)$$

Where,

L = number of levels of a design variable

n = number of design variables

The front spring, rear spring and component have three levels of stiffness viz. low, medium and high and the CG as variable has two levels viz. center and offset.

Thus, Number of iterations = $3^3 \times 2^1 = 27 \times 2 = 54$

The run matrix is as shown in Figure 4.

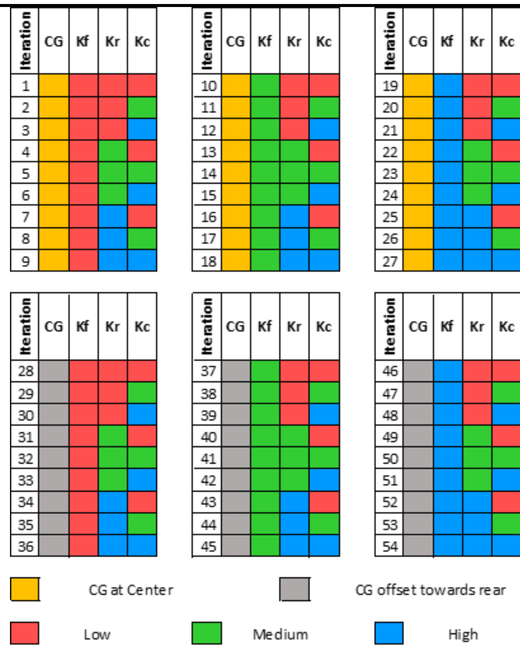


Fig. 4. Run matrix

The FE simulations are performed as per the above iterations and the results are then extracted.

Results

The results of the study are as discussed below. The graphs are generally plotted for two different conditions of CG, viz. CG at center and CG offset towards rear. Total spring stiffness (K) depicts the stiffness of packaging foam and is equivalent to stiffness of front and rear springs combined.

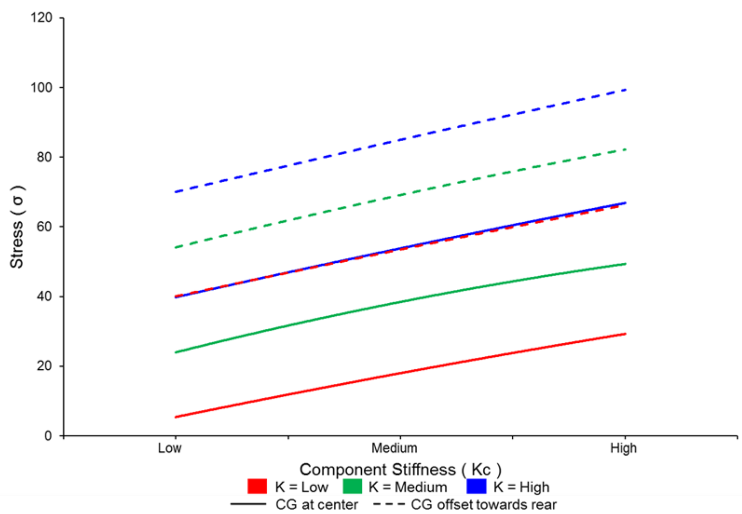


Fig. 5. Stress vs Component stiffness

Figure 5 shows the variation of stress (σ) with component stiffness (K_c) when K varies from low to high, for both conditions of CG. It is observed that stress increases with increase in component stiffness. Also, stress is relatively more when CG is offset towards rear as compared to when CG is at center.

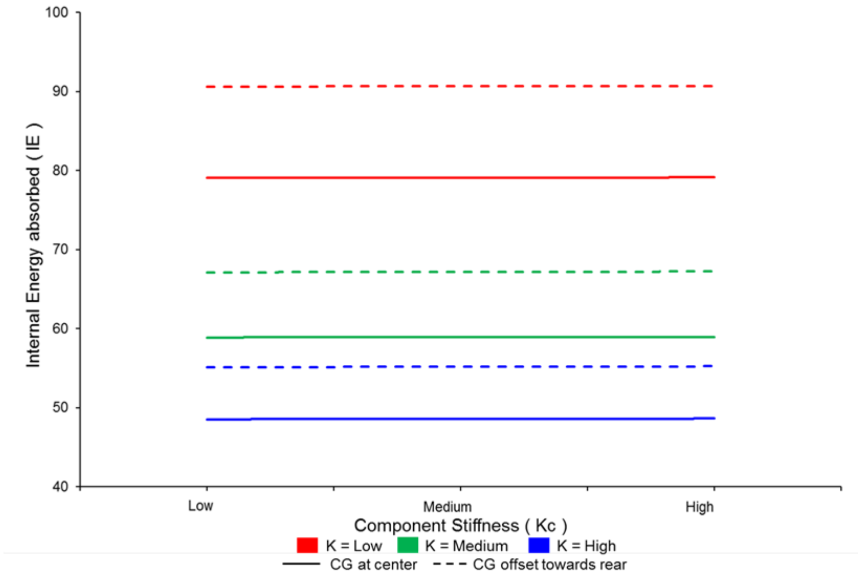


Fig. 6. Internal energy absorbed vs Component stiffness

Figure 6 shows the variation of internal energy absorbed (*IE)* with component stiffness (K_c) when K varies from low to high, for both conditions of CG. It is observed that total internal energy absorbed by foam is independent of variation in component stiffness. *IE* is inversely proportional to total spring stiffness (K) for a constant value of K_c and is relatively more when CG is offset towards rear as compared to when CG is at center.

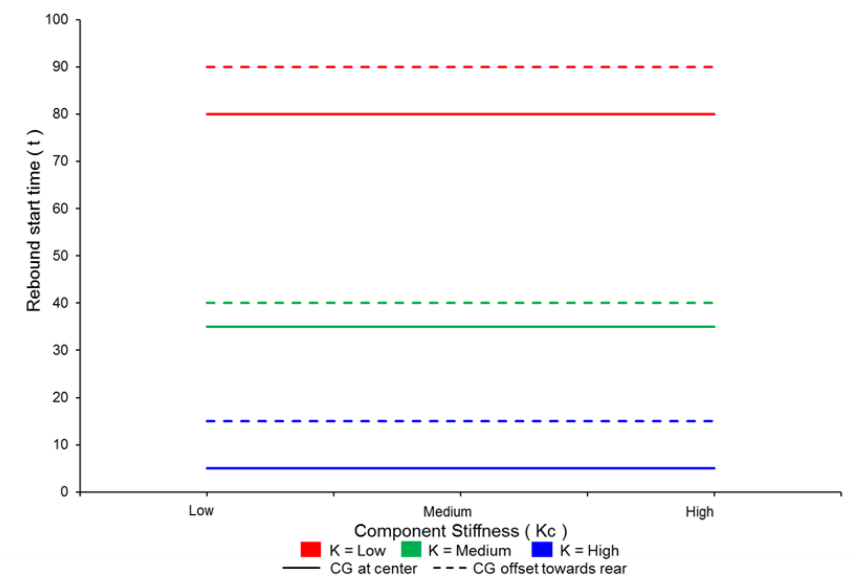


Fig. 7. Rebound start time vs Component stiffness

Figure 7 shows the variation of rebound start time (t) with component stiffness (K_c) when K varies from low to high, for both conditions of CG. It is observed that rebound start time is independent of variation in component stiffness. Rebound start time is inversely proportional to total spring stiffness (K) for a constant value of K_c and is relatively more when CG is offset towards rear as compared to when CG is at center.

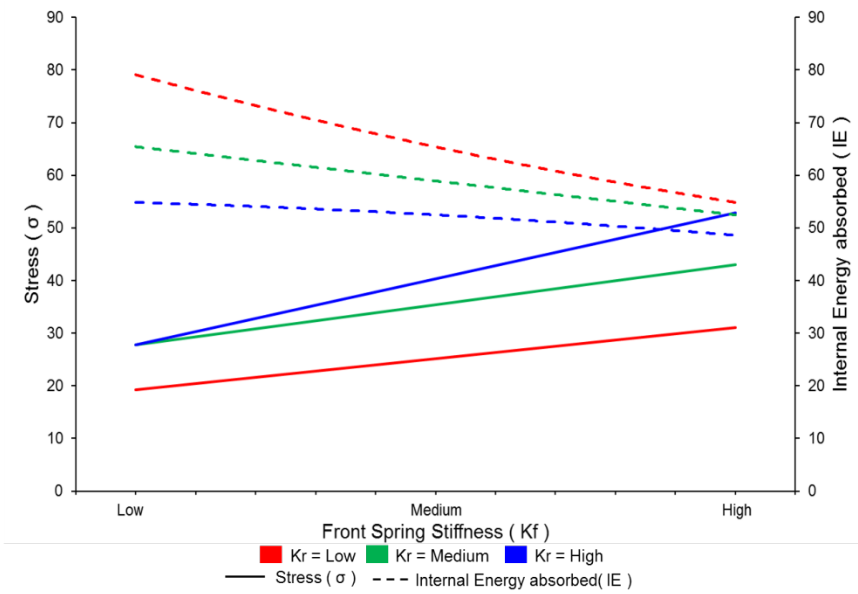


Fig. 8. Stress and Internal energy absorbed vs Front spring stiffness when CG is at center

Figure 8 shows the variation of stress *(σ)* and internal energy absorbed (*IE)* with front spring stiffness (K_f) respectively, when rear spring stiffness (K_r) varies from low to high, for CG at center. It is observed that stress is directly proportional to stiffness of both springs (K_f and K_r). Also, IE is inversely proportional to stiffness of both springs (K_f and K_r). As the CG of the component is at center, the nature of the plot will remain same for σ vs K_r and *IE* vs K_r when K_f varies from low to high.

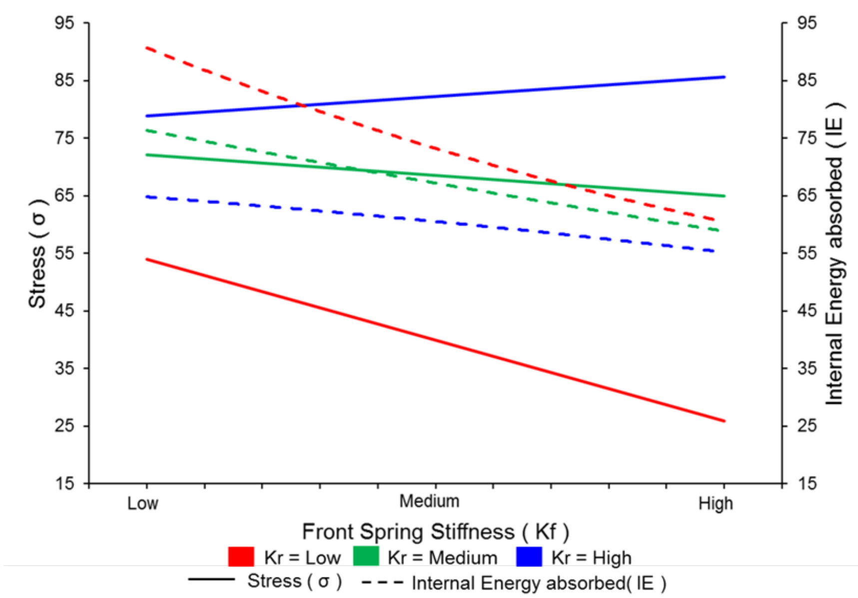


Fig. 9. Stress and Internal energy absorbed vs Front spring stiffness when CG is offset towards rear

Figure 9 shows the variation of stress *(σ)* and internal energy absorbed (*IE)* with front spring stiffness (K_f) respectively, when rear spring stiffness (K_r) varies from low to high, for CG offset towards rear. It is observed that the slope of stress vs K_f (for typical K_r value) varies from negative to positive as K_r increases. For a particular value of K_r, the slope is zero i.e. stress is independent of K_f. Stress is directly proportional to K_f above that value and inversely proportional below that value. Also, *IE* is inversely proportional to stiffness of front spring (K_f).

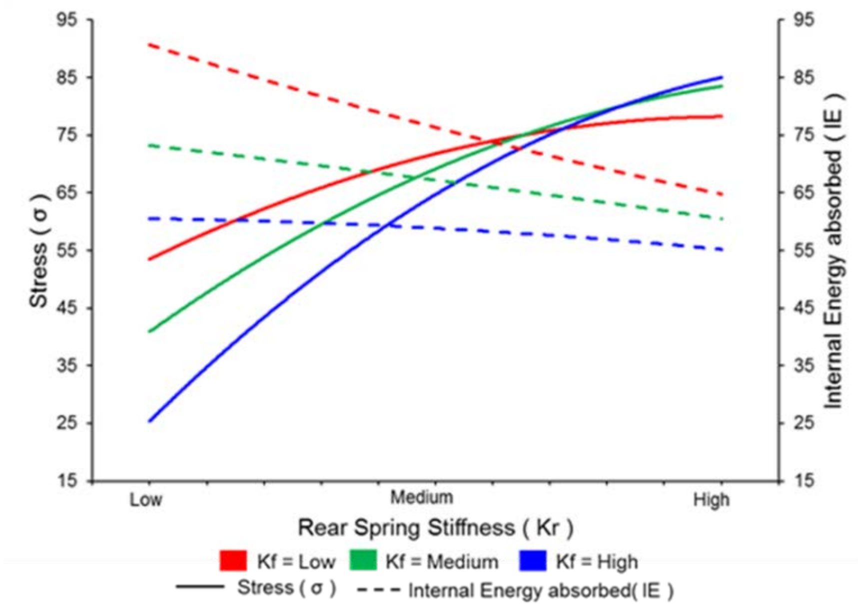


Fig. 10. Stress and Internal energy absorbed vs Rear spring stiffness when CG is offset towards rear

Figure 10 shows the variation of stress (σ) and internal energy absorbed (*IE)* with rear spring stiffness (K_r) respectively, when front spring stiffness (K_f) varies from low to high, for CG offset towards rear. It is observed that stress is directly proportional to stiffness of rear springs (K_r). Also, IE is inversely proportional to stiffness of rear springs (K_r).

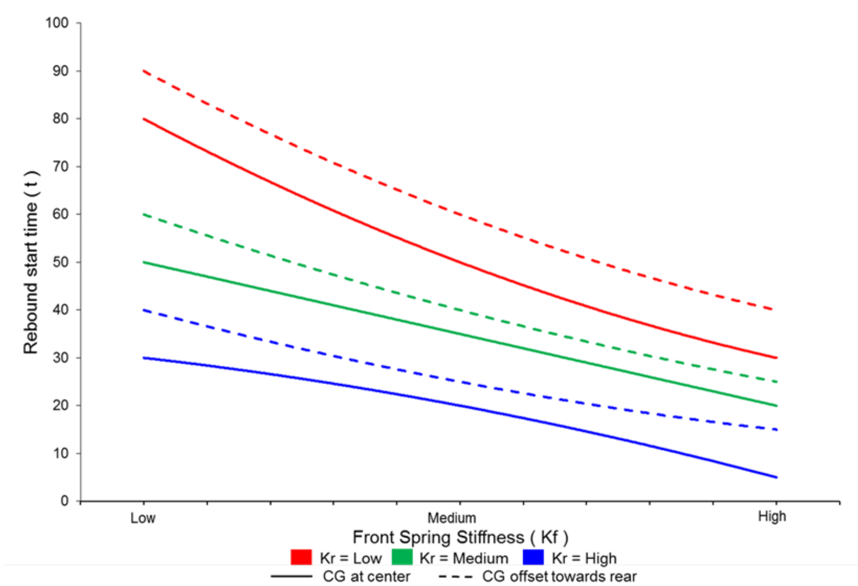


Fig. 11. Rebound start time vs Front spring stiffness

Figure 11 shows the variation of rebound start time (*t)* with front spring stiffness (K_f), when rear spring stiffness (K_r) varies from low to high, for both conditions of CG. It is observed that as the front spring stiffness (K_f) increases the rebound start time (*t*) decreases i.e. they are inversely proportional to each other. Also, rebound start time is relatively more when CG is offset towards rear as compared to when CG is at center.

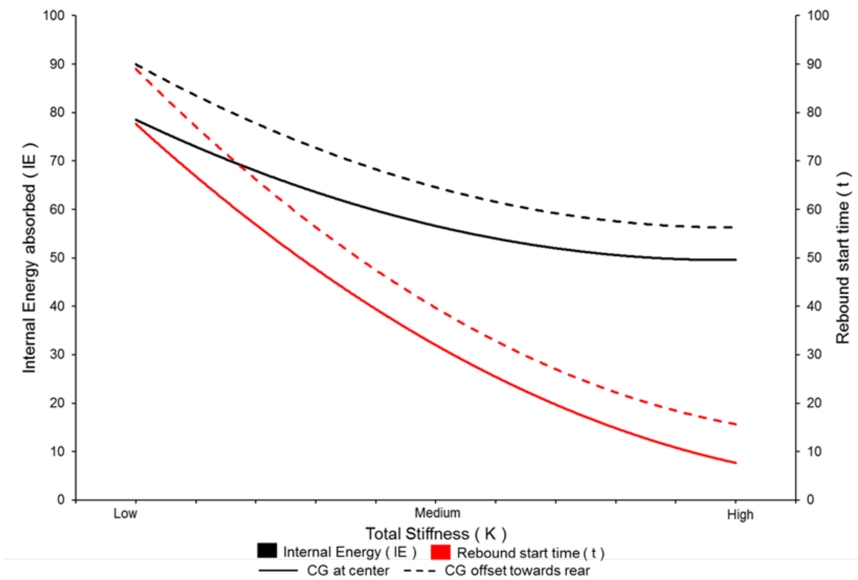


Fig. 12. Internal energy absorbed and Rebound start time vs Total spring stiffness

Figure 12 shows the variation of internal energy absorbed (*IE)* and rebound start time (*t)* with total spring stiffness (*K*) for both conditions of CG. It is observed that *IE* is inversely proportional to total spring stiffness (*K*). Also, as stiffness of foam (*K*) will increase, time to reach minimum kinetic energy (*t*) will decrease. Both *IE* and *t* are relatively more when CG is offset towards rear as compared to when CG is at center.

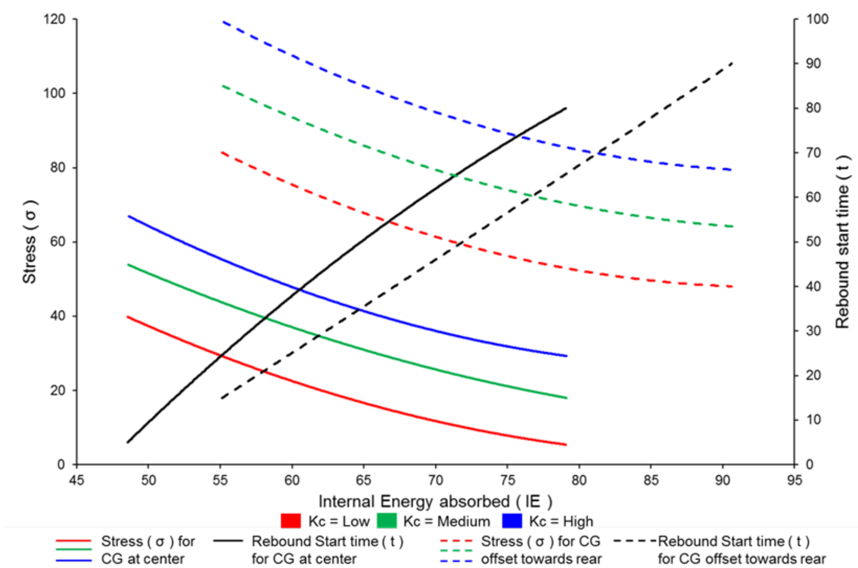


Fig. 13. Stress and Rebound start time vs Internal energy absorbed

Figure 13 shows the variation of stress (*σ)* and rebound start time (*t)* with internal energy absorbed (*IE*), when component stiffness (K_c) varies from low to high, for both conditions of CG. It is observed that stress and *IE* are inversely proportional whereas rebound start time and *IE* are directly proportional to each other. Also, for constant *IE*, component stiffness (K_c) has no effect on rebound start time (*t*). The same has been depicted in Figure 7 also. Stress increases as K_c increases for constant *IE*. Moreover, when CG is offset, stress is more and rebound start time (*t*) is less for same *IE.*

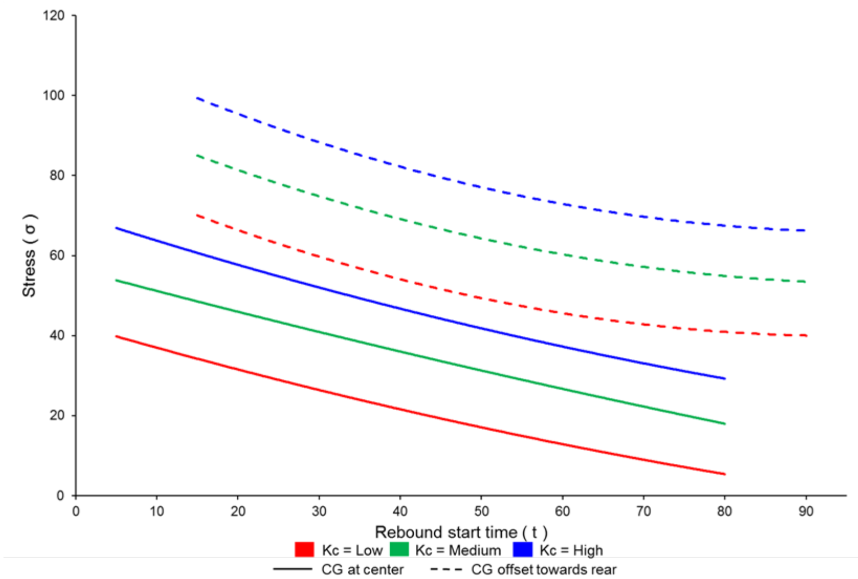


Fig. 14. Stress vs Rebound start time

Figure 14 shows the variation of stress (σ) with rebound start time (t), when component stiffness (K_c) varies from low to high, for both conditions of CG. It is observed that, stress (σ) and rebound start time (t) are inversely proportional to each other. Also, rebound start time is relatively more for same component stiffness (K_c) when CG is offset towards rear.

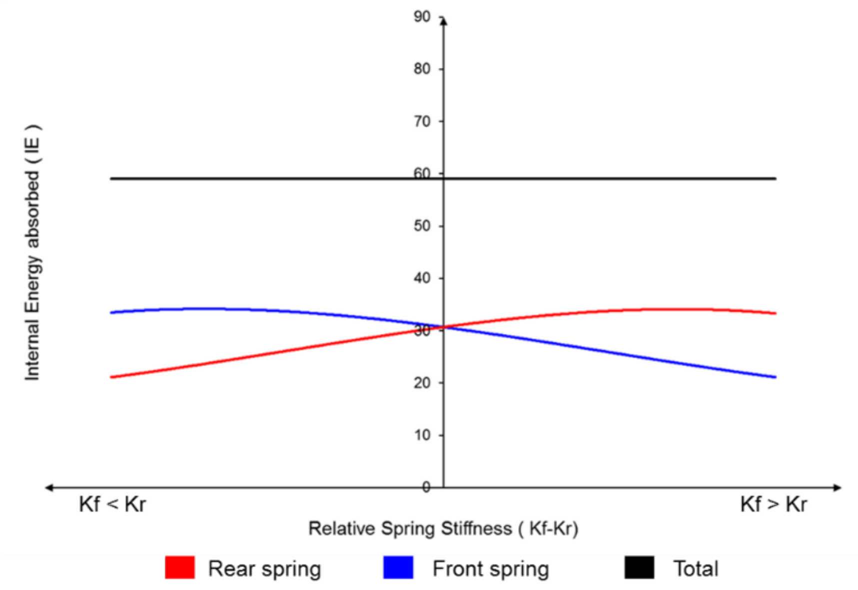


Fig. 15. Internal energy absorbed vs Relative spring stiffness when CG is at center

Figure 15 shows the variation of internal energy absorbed (*IE)* with relative spring stiffness ($K_f - K_r$), when CG is at center. It is observed that, for K_r=K_f, both springs absorb equal portion of the total *IE*; while, for $K_f > K_r$, rear spring absorbs more portion of total *IE* than front spring and vice versa.

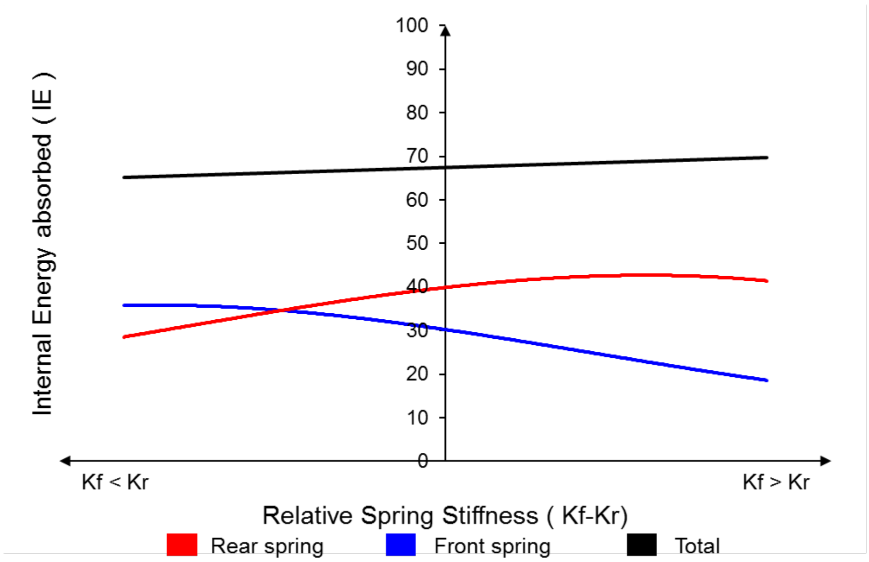


Fig.16. Internal energy absorbed vs Relative spring stiffness when CG is offset towards rear

Figure 16 shows the variation of internal energy absorbed (*IE)* with relative spring stiffness ($K_f - K_r$), when CG is offset towards rear. It is observed that, for K_r=K_f, and $K_f > K_r$, rear spring absorbs more portion of the total *IE* as compared to front spring. Moreover, for $K_f < K_r$, rear spring will absorb more energy than front spring up to a certain point. At this point, both springs will absorb same energy. After this point, as K_r increases relative to K_f, energy absorbed by front spring is more than the rear spring.

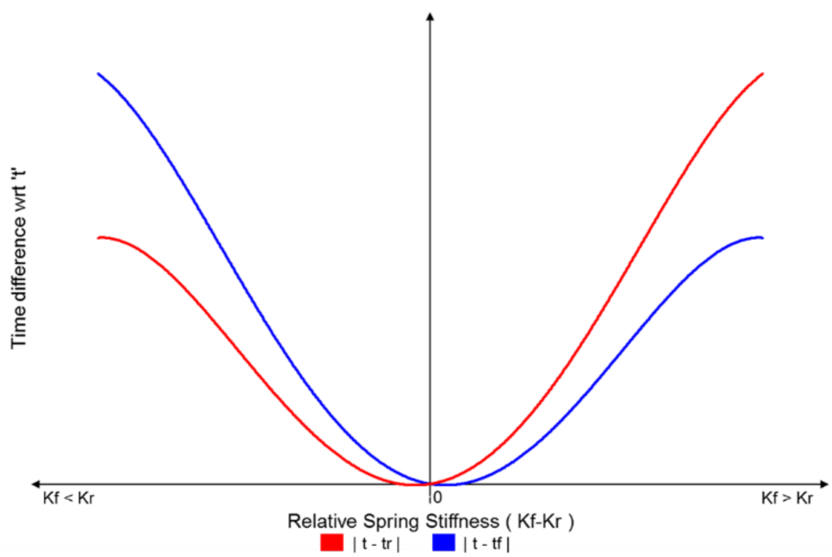


Fig. 17. Time difference with respect to 't' vs Relative spring stiffness when CG is at center

Figure 17 shows the variation of time difference with respect to '*t*' with Relative Spring Stiffness (K_f - K_r), when CG is at center. Time difference with respect to '*t*' for a spring is the difference between time at maximum internal energy of the system and that of the corresponding spring. It is observed that, for $K_f = K_r$, the internal energy absorbed by both springs is equal and they reach their peak values at the same time i.e. $t = t_f = t_r$, where, t_f is the time at maximum IE_f during the cycle and t_r is the time at maximum IE_r during the cycle. For $K_f > K_r$, time difference of t_f with respect to t ($|t - t_f|$) is less. Thus, t_f is closer to t, i.e. K_f is more influential on t. Moreover, for $K_f < K_r$, time difference of t_r with respect to t ($|t - t_r|$) is less. Therefore, t_r is closer to t, i.e. K_r

is more influential on t. As a result, for the spring whose stiffness is more, its time will be closer to the time of minimum kinetic energy t i.e. the time when rebound starts. Also, when difference between stiffness of the springs is more, peak time of *IE* of either spring (t_f or t_r) will be farther as compared to time of total *IE (t).*

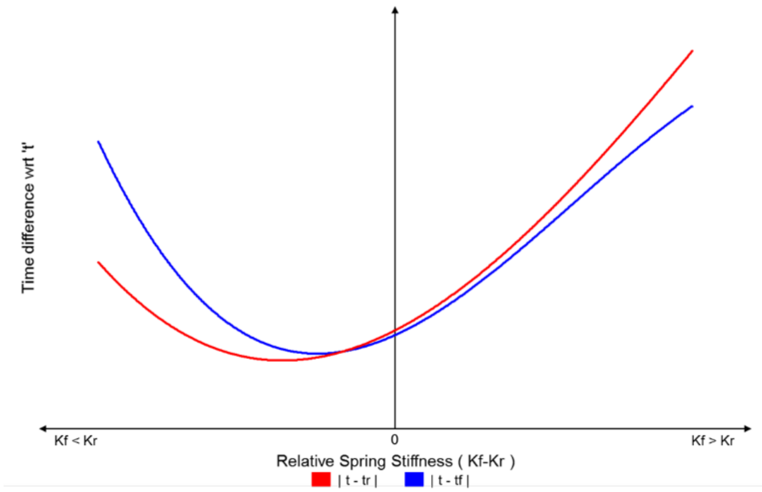
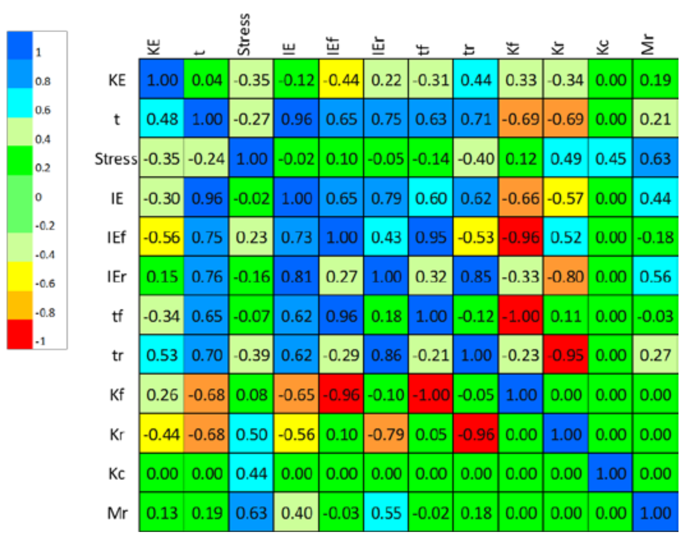


Fig.18. Time difference with respect to 't' vs Relative spring stiffness when CG is offset towards rear

Figure 18 shows the variation of time difference with respect to 't' with relative spring stiffness (K_f - K_r), when CG is offset towards rear. It is observed that, for $K_f > K_r$, time difference of t_f with respect to t viz. ($|t - t_f|$) is less. Thus, t_f is closer to 't' i.e. K_f is more influential on t. For $K_f < K_r$, time difference of t_r with respect to t viz. ($|t - t_r|$) is less. Therefore, t_r is closer to t, i.e. K_r is more influential on t. As a result, for the spring whose stiffness is more, its time will be closer to the time of minimum kinetic energy t i.e. the time when rebound starts. However, as the mass is offset towards rear, the point when t_f and t_r are closest to t has shifted from center towards rear. Also, the difference between the curves is more when $K_r > K_f$ as compared to when $K_f > K_r$.

Correlation Matrix

The matrix as shown in Figure 19 depicts the correlation factors between various input variables and output parameters. Correlation factors range from -1 to 1, where -1 indicates strong negative relationship and 1 indicates a strong positive relationship. The value 0 indicates no correlation.



	KE	t	Stress	IE	IEf	IEr	tf	tr	Kf	Kr	Kc	Mr
KE	1.00	0.04	-0.35	-0.12	-0.44	0.22	-0.31	0.44	0.33	-0.34	0.00	0.19
t	0.48	1.00	-0.27	0.96	0.65	0.75	0.63	0.71	-0.69	-0.69	0.00	0.21
Stress	-0.35	-0.24	1.00	-0.02	0.10	-0.05	-0.14	-0.40	0.12	0.49	0.45	0.63
IE	-0.30	0.96	-0.02	1.00	0.65	0.79	0.60	0.62	-0.66	-0.57	0.00	0.44
IEf	-0.56	0.75	0.23	0.73	1.00	0.43	0.95	-0.53	-0.96	0.52	0.00	-0.18
IEr	0.15	0.76	-0.16	0.81	0.27	1.00	0.32	0.85	-0.33	-0.80	0.00	0.56
tf	-0.34	0.65	-0.07	0.62	0.96	0.18	1.00	-0.12	-1.00	0.11	0.00	-0.03
tr	0.53	0.70	-0.39	0.62	-0.29	0.86	-0.21	1.00	-0.23	-0.95	0.00	0.27
Kf	0.26	-0.68	0.08	-0.65	-0.96	-0.10	-1.00	-0.05	1.00	0.00	0.00	0.00
Kr	-0.44	-0.68	0.50	-0.56	0.10	-0.79	0.05	-0.96	0.00	1.00	0.00	0.00
Kc	0.00	0.00	0.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
Mr	0.13	0.19	0.63	0.40	-0.03	0.55	-0.02	0.18	0.00	0.00	0.00	1.00

Fig. 19. Correlation matrix

Where,
M_r = Mass acting on rear side for the condition in which CG is offset towards rear.

Conclusion

It can be concluded from the study that front spring stiffness (K_f), rear spring stiffness (K_r), total spring (packaging foam) stiffness (K) and stress (σ) each have negative relationship with both total internal energy absorbed (IE) and rebound start time (t) for both conditions of CG. Total internal energy absorbed (IE) and rebound start time (t) have positive relationship with each other for both conditions of CG. Rear spring stiffness (K_r) and component stiffness (K_c) both have positive relationship with stress (σ) for both conditions of CG. Front spring stiffness (K_f) and total spring (packaging foam) stiffness (K) both have positive relationship with stress (σ) when CG is at center, but have mixed relationship varying between positive and negative when CG is offset towards rear. Total internal energy absorbed (IE) and rebound start time (t) are independent of variation in component stiffness (K_c). Table 1 and Table 2 summarize the results of this study when CG is at center and when CG is offset towards rear respectively.

Table 1. Results summary (CG at Center)

	Stress (σ)	***Total internal energy absorbed (IE)***	***Rebound start time / Time at minimum kinetic energy (t)***
Front spring stiffness (K_f)	Positive	Negative	Negative
Rear spring stiffness (K_r)	Positive	Negative	Negative
Total spring (foam) stiffness (K)	Positive	Negative	Negative
Component stiffness (K_c)	Positive	Independent	Independent
Stress (σ)	-	Negative	Negative
Total internal energy absorbed (IE)	Negative	-	Positive
Rebound start time / Time at minimum kinetic energy (t)	Negative	Positive	-

Table 2. Results summary (CG Offset)

	Stress (σ)	***Total internal energy absorbed (IE)***	***Rebound start time / Time at minimum kinetic energy (t)***
Front spring stiffness (K_f)	Mixed	Negative	Negative
Rear spring stiffness (K_r)	Positive	Negative	Negative
Total spring (foam) stiffness (K)	Mixed	Negative	Negative
Component stiffness (K_c)	Positive	Independent	Independent
Stress (σ)	-	Negative	Negative
Total internal energy absorbed (IE)	Negative	-	Positive
Rebound start time / Time at minimum kinetic energy (t)	Negative	Positive	-

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