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Modeling of the Bumper as an Impact Attenuation Device

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Abstract—The bumper of a road vehicle is designed for very low speed impacts (4 km/h). To improve on this there is the need for an approapriate mathematical model of the bumper, which is very responsive in the changes in the characteristics of the bumper material, to be used in investigating and finding better materials for this purpose**.** Four models, namely, the Maxwell, Kelvin and two Solid or Hybrid models, were used to simulate the bumper in a barrier test to obtain the responses of the displacement, velocity and acceleration. The results were compared with those of a standard crash test used by automobile manufacturers which is higher than that required by law, the NCAP test, a standard crash test for a vehicle in a Full width barrier test. The results were then discussed in line with desired behavior.

It was observed that the acceleration response of the Maxwell, Hybrid 1 and Hybrid 2 models have zero deceleration at time zero, similar to the NCAP test results, however, the Kelvin model gave a non-zero initial acceleration. It was also observed that the displacement, velocity and acceleration responses of the Maxwell model deviates completely from the NCAP test crash plot. The relevant part from the plots of the responses of the Kelvin, Hybrid 1 and Hybrid 2 models, were similar to the behaviour of the NCAP test plot. The three models had damped sinusoidal curves for both the displacement and velocity responses.

As far as changes in maximum displacement, rebound velocity and maximum acceleration are concerned, the Kelvin model showed higher responsiveness to changes introduced as a result of changes in material properties than the two hybrid models. The Kelvin model was selected and modified for a better impact attenuation.

Index Terms— Impact attenuation, hybrid model, visco-elastic material, bumper, mathematical model, solid model, Maxwell model, Kelvin model, Hybrid model

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1 Introduction

The bumpers of most vehicles are made basically of visco-elastic materials (Huang, 2002). The Maxwell, Kelvin models and the Solid or Hybrid models, can be used to model this behaviour. These models make use of a spring and a viscous damper.

There have been proposals and use of integration of impact sensors and exterior airbags to reduce impacts in road traffic crashes (Schuster, 2004). But these require an external source of energy to function. In this study, the bumper, a visco-elastic passive damper system (Lametrie, 2001) is proposed for attenuating impact energy.

The Maxwell, Kelvin and two Solid or Hybrid models (Fung and Tong, 2001), which are variants of the first two, were used to model the behavior of a road vehicle bumper. The modeling and simulation of the bumper using VisSim™ software, a fast and easy-to-use dynamic simulation and model-based system development software (VSI, 2012) and data extraction from the simulation for design purposes are described.

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2 Problem statement

Road traffic crashes posses a big global problem. It is ranked ninth globally among the leading causes of disease burden, in terms of Disability Adjusted Life Years (DALYs) lost (Odero, 2006).

In the United States it is estimated that road traffic accidents claim a life every thirteen minutes (Zheng, 2006). The direct economic costs of global road crashes, has been estimated at US$ 518 billion (Peden et al., 2004).

The bumper of road vehicles are designed for very low speed impacts (4 km/h). Impacts resulting from vehicles travelling at medium speeds (50 km/h) therefore cannot be attenuated by the bumper. It would be very desirable if vehicle bumpers could absorb part of the crash impact to protect the occupants of the vehicle. To do this there is the need to investigate and use materials that could serve this purpose. There is therefore the need for a mathematical model of the bumper that is very responsive in the changes in the characteristics of the bumper material to be used in investigating and proposing better materials for this purpose**.**

3 Objectives

1. Evaluate different mathematical models for the road

vehicle bumper.

2. Find the model that is more responsive to changes in the material characteristics of the bumper..
3. Select an appropriate model for design purposes.

4 The Models

The Maxwell Model consists of a spring and a dashpot connected in series and the Kelvin model consists of a spring and a dashpot connected in parallel (Huang, 2002). Figures 1(a) and 1(b) show schematic diagrams of the Maxwell and Kelvin models respectfully.

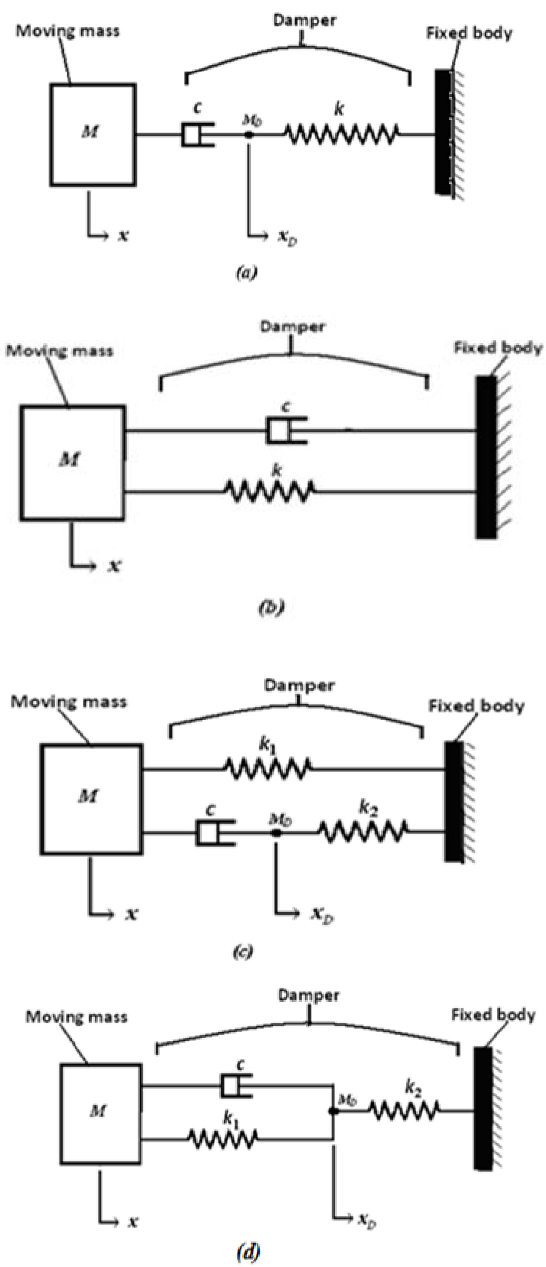

Fig. 1 Schematic of the Maxwell (a), Kelvin (b), Hybrid 1 (c) and Hybrid 2 (d) Models (Huang, 2002).

Two types of hybrid models were considered, Hybrid 1 model and Hybrid 2 model as shown in Figures 1 (c) and 1 (d) respectively. The Hybrid models combine the Kelvin and Maxwell models making use of two springs and a dashpot. Hybrid 1 model combines a spring k_1 in parallel with the Maxwell model while Hybrid 2 model combines the Kelvin model in series with a spring, k_2. Equations of motion for the models can be derived as, (Huang, 2002):

For the Maxwell model,

$$\dddot{x} + {}^{k}\!/_{c}\,\ddot{x} + {}^{k}\!/_{M}\,\dot{x} = 0 \qquad (1)$$

$$M\ddot{x} + c\dot{x} + kx = 0 \qquad (2)$$

For the Hybrid 1 model,

$$\dddot{x} + \frac{k_2}{c}\ddot{x} + \left(\frac{k_1 + k_2}{M}\right)\dot{x} + \frac{k_1 k_2}{cM}x = 0 \qquad (3)$$

For the Hybrid 2 model,

$$\dddot{x} + \left(\frac{k_1 + k_2}{c}\right)\ddot{x} + \frac{k_2}{M}\dot{x} + \frac{k_1 k_2}{cM}x = 0 \qquad (4)$$

Where x is deflection of the mass; k, k_1 and k_2 are spring constants; c is damping coefficient of the damper; M is mass of a moving body; and M_D is a negligible mass.

5 Method

The responses of displacement, velocity and acceleration for the four models were discussed in line with desired behaviour to evaluate them, and select the most responsive one for modeling the bumper for crash considerations. These graphs are compared with a plot of a standard crash test data used by U.S. automobile manufacturers, the New Car Assessment Program (NCAP) test, which is higher than that required by law (NHTSA, 2007), for evaluation. The NCAP test is a standard crash test for a vehicle in a Full width barrier test (Leneman et al., 2004).

Figure 2 shows typical results for a vehicle in a Full width barrier NCAP test.

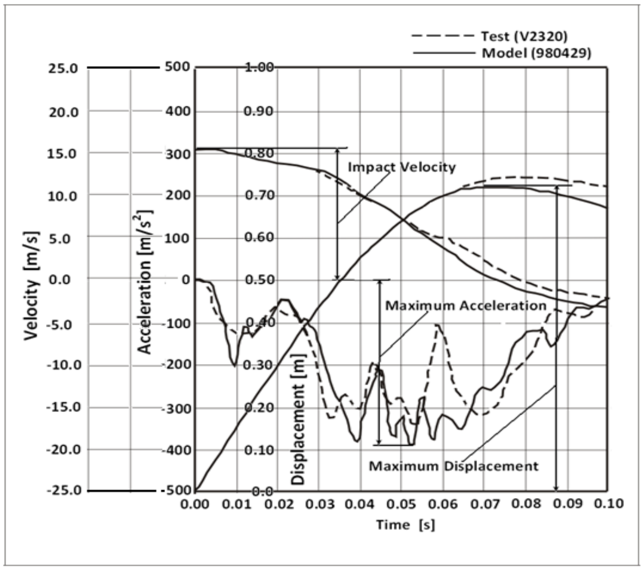

Fig. 2 Expected Response of a Barrier Crash Test (Leneman et al., 2004)

The plots were compared with the responses of the various models to help in their evaluation. A range of material properties was considered in this study. The material properties under consideration here were the spring constant and the damping coefficient. The spring constant ranges from a low stiffness value of k^*_1 to a high stiffness value of k^*_2 while the damping coefficient ranges from a low damping value of c^*_1 to a high damping value of c^*_2. The choice was made based on practical values of the material properties of a small car (Sedan Car) and a relatively bigger car (Sport Utility Van (SUV)). The general material properties considered were as follows (Huang, 2002):

SUV: k = 4339 lb/in and c = 83.2 lb-s/in

Sedan Car: k = 2474 lb/in and c = 41.7 lb-s/in

In order to evaluate the models to cover the range of k's and c's, a high value of k^*_2 = 5000 lb/in and low value of k^*_1 = 2000 lb/in were selected. Also the range of damping coefficients selected was from c^*_1 = 40 lb-s/in to c^*_2 = 85 lb-s/in. In SI units, c^*_1 = 7005.3 N-s/m, c^*_2 = 14886 N-s/m, k^*_1 = 350270 N/m, and k^*_2 = 875670 N/m. This range of material properties defines the region under study. Figure 3 shows the region or range of material properties considered in this study. The behaviour of the responses of the four models is evaluated within this spectrum of material properties. In the evaluation, $k^*_n c^*_n$ implies a combination of spring constant k^*_n and damping coefficient c^*_n; where n = 1, 2. Thus, the combination $k^*_1 c^*_1$ corresponds to design point 1. The combination $k^*_1 c^*_2$ corresponds to design point 2; while $k^*_2 c^*_1$ corresponds to design point 3 and $k^*_2 c^*_2$ corresponds to design point 4 of the region under study as shown in Figure 3. These points were used in the simulation processes.

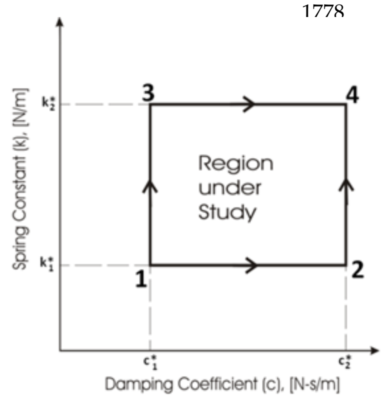

Fig. 3 Range of Material Properties for the Study

Simulations were performed for the four models using the design parameters at the design points. The responses are discussed in the next sections; that is the displacement, velocity and acceleration responses.

6 Results

6.1 Displacement Response

Figure 4 gives the displacement responses of the various models. Equations of motion for the models were used in the simulation. VisSim™ software was used in the simulation to solve the differential equations. Information from these plots is summarized in Tables 1.

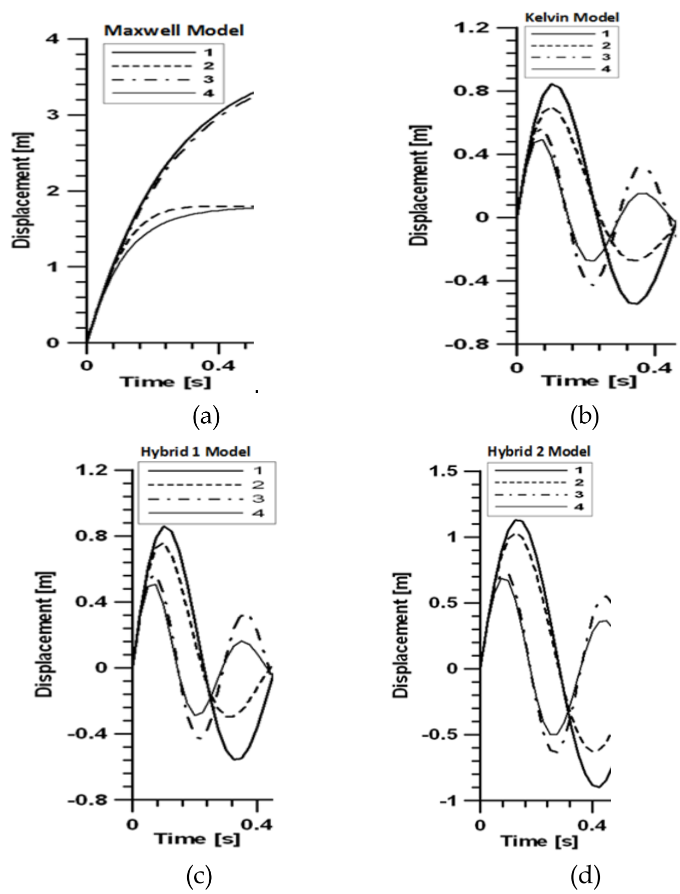

Fig. 4 Displacements at the four (4) design points for the Models

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Table 1 Maximum Displacement (x), Rebound Velocity (v), Maximum Acceleration (a), and Duration of Pulse (t) for the Models at the Four Design Points

(a)

	Maxwell Model			
D.P.	x	v	a	t
1	3.80	-	-43.8	1.5
2	1.80	-0.1	-76.2	0.5
3	3.80	–	-47.3	1.5
4	1.79	–	-87.7	0.75

(b)

	Kelvin Model			
D.P.	x	v	a	t
1	0.84	-9.3	-159.1	0.21
2	0.70	-6.4	-152.3	0.19
3	0.58	-10.5	-259.1	0.14
4	0.49	-8.2	-245.5	0.13

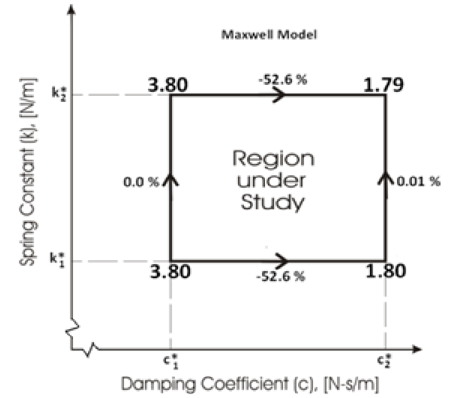
(c)

	Hybrid 1 Model			
D.P.	x	v	a	t
1	0.86	-9.6	-168.2	0.21
2	0.76	-7.5	-186.4	0.18
3	0.58	-10.7	-263.6	0.13
4	0.51	-8.9	-272.7	0.13

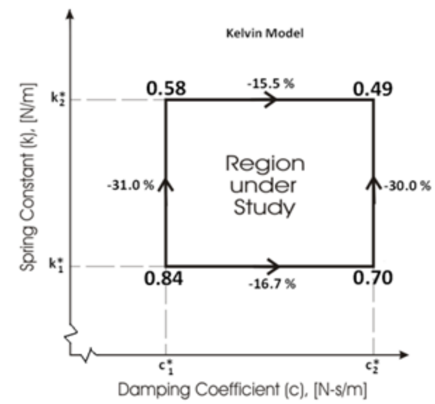
(d)

	Hybrid 2 Model			
D.P.	x	v	a	t
1	1.13	-11.4	-140.0	0.26
2	1.04	-9.5	-136.7	0.25
3	0.73	-12.0	-226.7	0.17
4	0.70	-10.5	-223.3	0.16

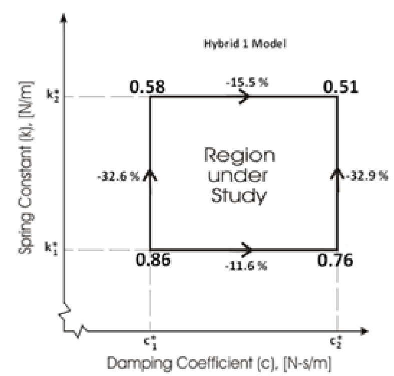
Tables 1 (a) to (d) contains the respective information on the maximum displacements, while Figures 5 (a) to (d) show the change in the maximum displacement as a result of changes in



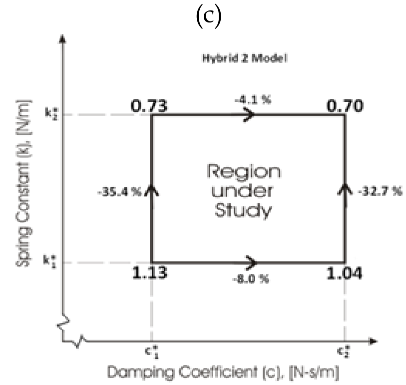
(a)



(b)



(c)



(d)

Fig. 5 Maximum Displacement at design points and effects of moving from one design point to the other for the four

Models.

properties for the four models. Maximum Displacements at design points are given at the respective corners of the region under study and the effects of moving from one design point to the other are given as a percentage (%) on the arrows.

6.2 Velocity Response

Figure 6 gives the velocity responses of the various models. Equations 1, 2, 3 and 4 were used in the simulation. Information from these plots is summarized in Tables 1 (a) to (d).

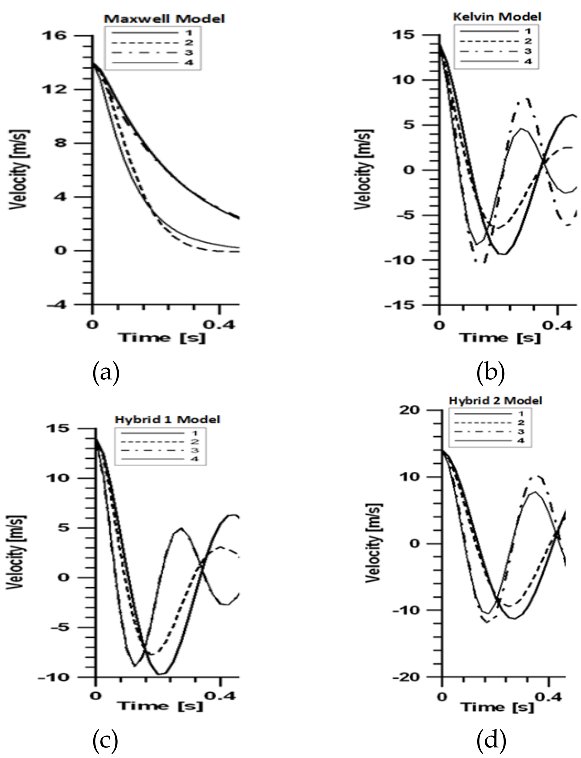


Fig. 6 Velocity at the four (4) design points for the Models

Tables 1 (a) to (d) give the respective information on the rebound velocity for the four models. Figure 7 shows rebound velocities at design points are given at the corners of the region under study and the effects of moving from one design point to the other are given as % on the arrows.

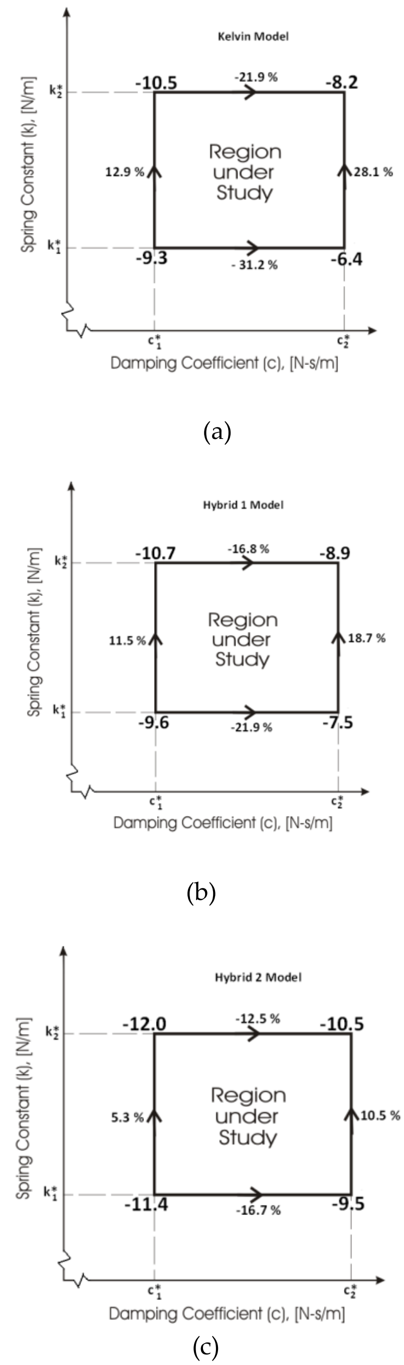


Fig. 7 Rebound Velocity at design points and effects of moving from one design point to the other for the Models.

6.3 Acceleration response

Figure 8 gives the acceleration responses of the various models. Equations 1, 2, 3 and 4 were used in the simulation. Information from these plots is summarized in Tables 1 (a) to (d).

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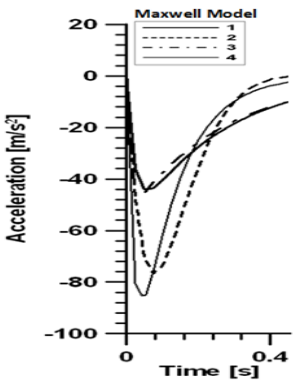
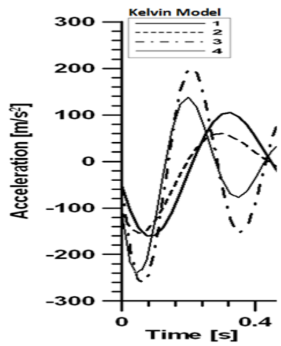
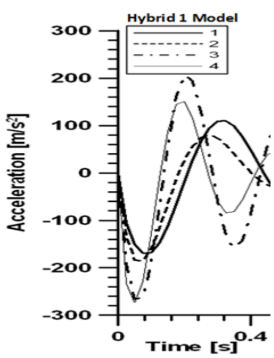


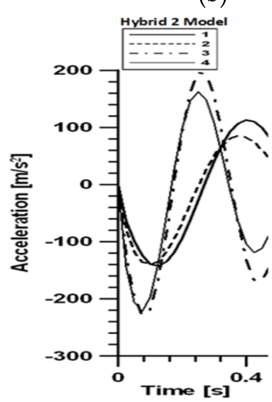
(a)



(b)



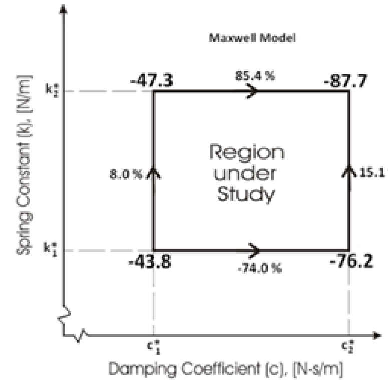
(c)



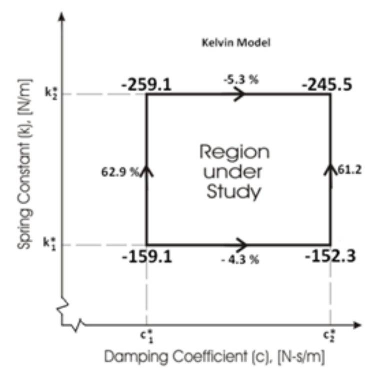
(d)

Fig. 8 Acceleration at the four (4) design points for the Models

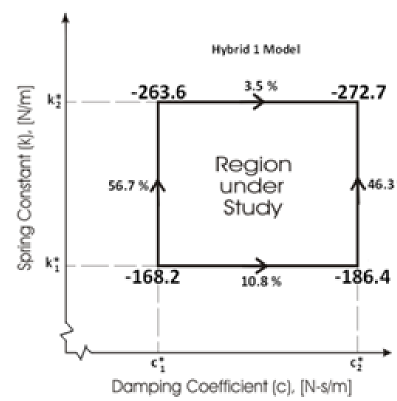
Table 1 contains the respective information on the maximum acceleration and the duration of the crash pulse, while the change in the maximum acceleration and the duration of the pulse as a result of changes in material properties for four models are shown in Figures 9 and 10 respectively. Maximum acceleration and duration of crash pulse at the design points are given at corners of the region under study and the effects of moving from one design point to the other are given as % on the arrows.



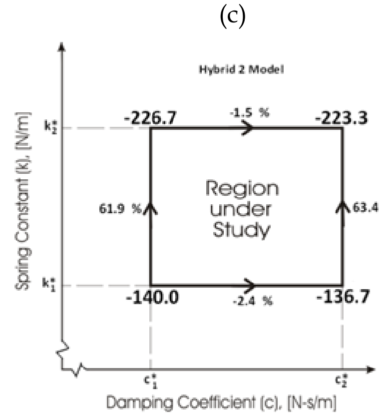
(a)



(b)

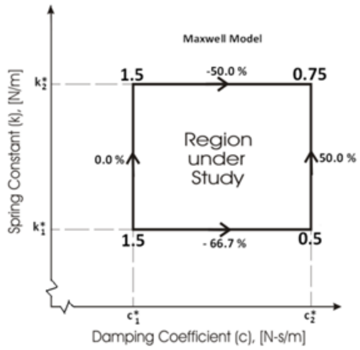


(c)

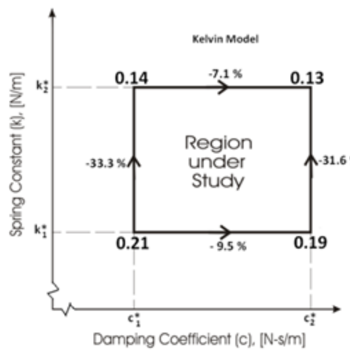


(d)

Fig. 9 Maximum Acceleration at design points and effects of moving from one design point to the other for the Models.



(a)



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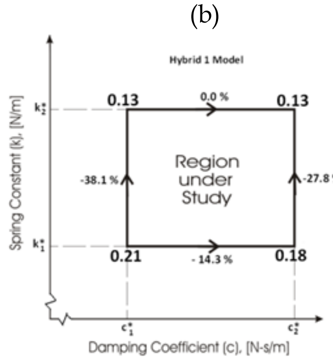

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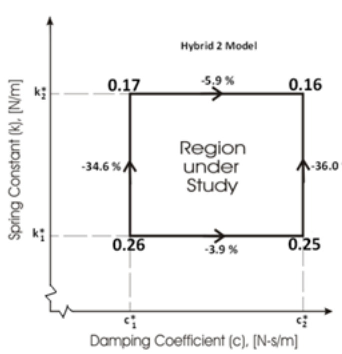

(d)

Fig. 10 Duration of Pulse at design points and effects of moving from one design point to the Models.

6.4 Discussion of results

The following observation can be made from the resulting responses:

i. The displacement and velocity responses of the Maxwell model (Figures 4(a) and 6(a)) deviates remarkably from the NCAP test crash plot in Figure 2. It does not show any rebound except for design point 2. This is expected since the damping coefficients are below the transition damping coefficient (c_T) except in the case of design point 2. i.e. when $c_T = \dfrac{\sqrt{Mk}}{2} > c$ (Huang, 2002).
The transition damping coefficient (c_T) is the minimum value of damping coefficient c, for which there is a dynamic crush at a finite time; and then the body rebounds afterwards (Huang, 2002).
The Maxwell model is therefore not good for this study as far as displacement and velocity responses are concerned.

ii. The displacement and velocity responses of the Kelvin, Hybrid 1 and Hybrid 2 models (Figures 4(b), 4(c) and 4(d) respectively for displacement and Figures 6(b), 6(c) and 6(d) respectively for velocity)) are damped sinusoidal curves. The first half cycle of the plots (which is the relevant part of the graphs) are similar to the behaviour of the NCAP test plot in Figure 2.

iii. From Figures 6 (b), (c) and (d), the Kelvin, Hybrid 1 and Hybrid 2 models all show an increase in rebound velocity for an increase in stiffness at constant damping; and a decrease in rebound velocity for an increase in damping coefficient at constant stiffness.

iv. From Figures 6 (b), (c) and (d), the Kelvin, Hybrid 1 and Hybrid 2 models all show a higher responsiveness to a change in damping coefficient at low stiffness (k^*_1) than at high stiffness (k^*_2).

v. The Kelvin, Hybrid 1 and Hybrid 2 models all show a higher responsiveness to a change in stiffness at higher damping coefficient (c^*_2) than at low damping coefficient (c^*_1).

vi. Comparatively the Kelvin model shows the highest level of responsiveness to changes in the damping coefficients and stiffness of the material, followed by the Hybrid 1 model and then the Hybrid 2 model as far as rebound velocity is concerned.

vii. From Figure 5(a), unlike the other three models, the Maxwell model is less responsive to changes in stiffness (0.0% and 0.01%) compared to changes in damping coefficient (-52.6%). For a given damping coefficient, a change in stiffness appears to have very little or no effect on the maximum displacement for the Maxwell model.

viii. From Figures 5(b), 5(c) and 5(d), at constant damping coefficient a change in stiffness causes a change of displacement between -30.0% (for Kelvin) and -35.4% (for Hybrid 2) in the Kelvin, Hybrid 1 and Hybrid 2 models, but only little change, i.e. between -4.1% (for Hybrid 2) and -16.7% (for Kelvin) for a change in damping coefficient at constant stiffness. This shows that a change in stiffness has a greater effect (about three times more) than a change in damping coefficient for all three models.

ix. Comparatively the Kelvin model shows much higher responsiveness to change in damping coefficient *c*, at a constant spring constant k^*, of the material by a difference of 5.1 % and 0.0 % for Hybrid 1 model at spring constants k^*_1 and k^*_2 respectively, and a difference of 8.7 % and 11.4 % for Hybrid 2 model at k^*_1 and k^*_2 respectively. However, the two hybrid models show slightly better responsiveness to change in spring constant at constant damping coefficient, c^*. That is a difference of only 1.6 % and 2.9 % for Hybrid 1 at constant c^*_1 and c^*_2 respectively; and 4.4 % and 2.7 % for Hybrid 2 model at constant c^*_1 and c^*_2 respectively.

x. The Maxwell, Hybrid 1 and Hybrid 2 models have zero deceleration at time zero, similar to the NCAP test results in Figure 2. The Kelvin model, however, has a non-zero deceleration at time zero, contrary to the NCAP test results in Figure 2.

xi. From Figure 9 all models show an increase in maximum deceleration for an increase in stiffness at constant damping. They show higher responsiveness to this change at high damping, c^*_2. Overall the Kelvin model shows higher responsiveness to changes in maximum deceleration due to changes in material properties.

7 Conclusion

A bumper should be well designed and have good energy absorption properties (Aylor et al., 2005), therefore a model to be used in its study and design should take care of the response to diverse material characteristics. In conclusion, the Kelvin model showed better responsiveness to changes in the material properties considered than all other models.

The Kelvin model is a second order differential equation which is simpler and easier to solve than the hybrid ones that are third order differential equations or coupled first and second order differential equations. The limitation of the Kelvin model, however, is that it produces a non-zero deceleration at time zero, a deviation from a crash pulse, which is typically zero at time zero. However, in spite of the non-zero initial value in the acceleration, the Kelvin model's pulse duration, and rebound velocities do not show significant reduction from those of the Hybrid 1 model. The Kelvin model was therefore chosen as the model for the Bumper for crash tests purposes.

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