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BRIEF TECHNICAL NOTE

Orientation-Dependent Impact Behavior of Polymer/EVA Bilayer Specimens at Long Wavelengths

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The net result of an impact on a structure is to generate a dynamic force, which is characterized by an amplitude ***P***, duration ***T***, and rate of loading ***1/t*** where ***t*** is the time to attain the peak force. Reduction in structural damage and injuries is typically sought by designing armors that reduce ***P*** and increasing ***t*** which essentially gives more time to the structure to respond to the dynamic threat [1–5]. Multilayer multi-material sections that are inter-spread with low density foams of varying densities are typically used to accomplish these goals [5–11]. Enormous work has been done in impact mechanics of multilayer system but highlighting those results are outside the scope of this note [12–16]. However, the bilayer effect discussed here is not covered in any of these papers. We report a surprising effect of sample orientation on the impact behavior of bilayer specimens made by bonding a 1–2 mm thick dense polymer layer (polyurea, polyurethane) to 10 mm thick EVA foam. The peak dynamic force was found to be dramatically different, by as much as 30–40 %, depending upon which face of the bilayer specimen bore the impact. The transmitted impact force was lowest when the dense polymer layer was in contact with the force transducer and the foam was directly hit from the top by the falling indenter. These observations have major implications for designing structures against dynamic loads with impulse duration in the 1–100 ms range that are ubiquitously encountered [11,17–19]. These observations cannot be explained using the wave mechanics principles that are based on the acoustic impedance mismatch between the two materials as the wavelength of the stress wave generated upon impact is in the 10–50 m range, which is much greater than the maximum specimen thickness of only 1.5 cm (Fig. 1)!

Sample Preparation and Experimental Procedure

Two types of samples were prepared. Type-A specimens were prepared using 25 mm diameter, 9 mm-thick, closed-cell EVA foam discs with density of 220 kg/m^3. Type-B samples used a different density EVA foam (32 kg/m^3) having a thickness and diameter of 13 mm and 25 mm, respectively. The top faces of both types of EVA samples were then separately bonded to a dense polymer film which covered the entire face of the EVA foam. Two different dense polymer films (polyurea and polyurethane) with two different thicknesses (1 mm and 1.5 mm), were used. Three specimens were prepared for each sample-type for studying the statistical variation. The polyurethane films were commercially obtained while polyurea films were prepared in the laboratory as described in [7–10].

Each specimen was tested by placing them on a 25 mm-diameter flat force plate and impacted using a drop-weight impact tester (Instron DynaTup, Model 8250). A 5 kg two-plate balanced mass attached to either side of a 76 mm-diameter flat stainless steel indenter head was dropped from a height of 61 mm such that the total kinetic energy at impact was 3J [6]. The transmitted force was measured by using a force transducer (Kistler Instruments, Model 9041A) with full scale output of 90 kN and sensitivity of 4.3 pC/N. To start, the EVA foam side was placed in contact with the force plate while the dense

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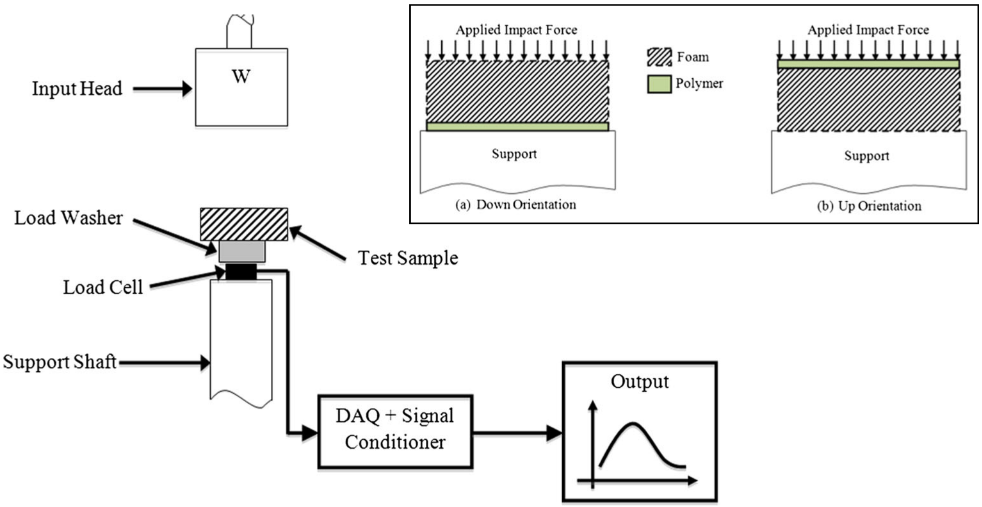
Fig. 1 Experimental setup [6]



polymer surface faced the falling impacter head (*Up* orientation). For each sample-type, measurements were also performed at impact energies of 5J and 7J by dropping the 5 kg mass through heights of 102 mm and 143 mm, respectively. Each specimen was impacted 20 times within a 2 min span to precondition the EVA foam as suggested by the ASTM-F1614 Test Method, 2006 [19]. A total of three impacts were carried out on the same specimen at the same energy, after it was preconditioned. The specimen was then flipped upside down such that the dense polymer film contacted the force plate (*Down* orientation). To eliminate variations stemming from material and manufacturing process variations, same sample was used for testing both orientations.

Results and Discussion

Figures 2, 3, and 4 show results for Type-A and Type-B samples. Each figure represents the average force-time response for both orientations for each specimen at different impact energies. Large differences in the peak force for the same *specimen* tested in both orientations under identical impact conditions (impact energy) can be visually spotted in these figures. This effect persists at both thicknesses (1 mm and 1.5 mm) of the polyurea and polyurethane films (Figs. 2, 3, and 4). Interestingly, the difference is much higher in Type-B samples which were prepared using a much lower density EVA foam. This can be seen by comparing data for the same polyurea or polyurethane sample in Figs. 2(a), (b), 3(a), (b), and 4(a), (b). The difference between the peak dynamic force is anywhere between 9 and 46 %. For example, the peak dynamic force of 4.05±0.21 kN for a 1.5 mm thick polyurea Type-A sample in the Up orientation is lowered to 2.85± 0.21 kN by flipping the specimen upside down when impacted by 5J energy (Fig. 3). The smallest difference in the peak force of 9 % was recorded in the Type-B sample with a 1 mm thick polyurethane film.

In general, data show that all specimens display a much stiffer response in the Down orientation as demonstrated by higher force values at lower times (1–2 ms) compared to the Up orientation. The force-time curve essentially develops a

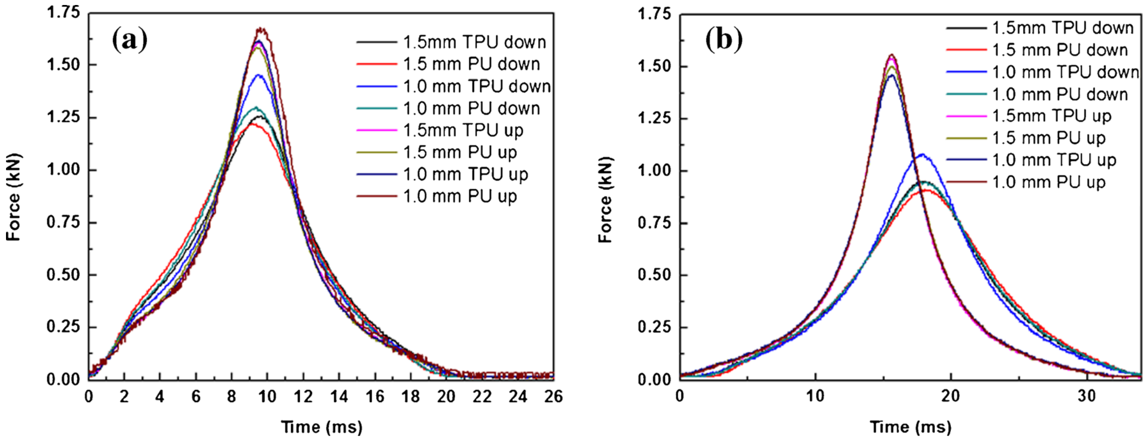


Fig. 2 Force-time history of (**a**) Type-A and (**b**) Type-B samples impacted by 3J energy (*TPU* thermoplastic polyurethane, *PU* polyurea)

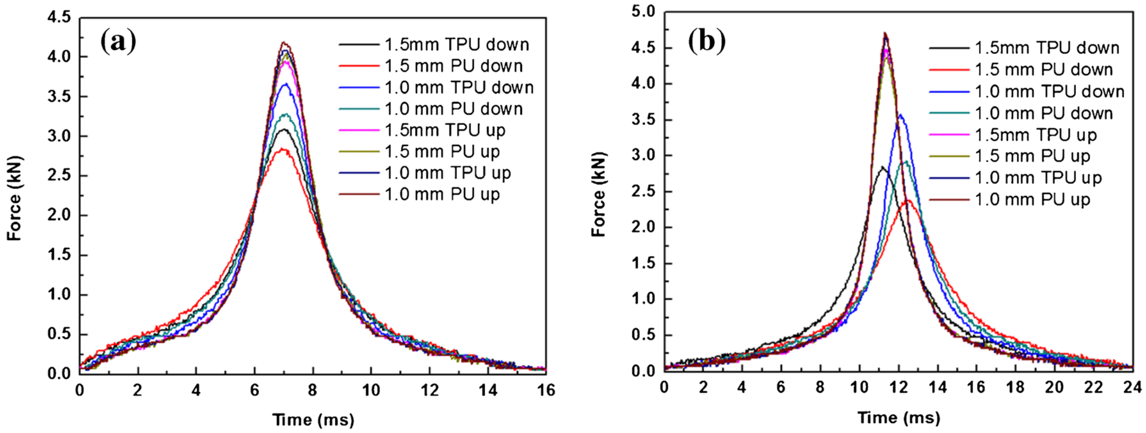


Fig. 3 Force-time history of (**a**) Type-A and (**b**) Type-B samples impacted by 5J energy (*TPU* thermoplastic polyurethane, *PU* polyurea)

shoulder for specimens tested in the Down orientation, while maintaining the same impulse duration ***T***. Moreover, samples with the polyurea film are more efficient in managing the impact as demonstrated by a lower peak force ranging from 15 to 30 % depending upon the impact condition. This can be seen by comparing peak force and corresponding percent reduction values in Table 1.

The observations of, (1) superior impact management by the polyurea film compared with the polyurethane layer, and (2) the said flipping effect becoming more pronounced by use of a lower density EVA foam, provide a clue regarding the possible mechanism for the observed effect. When the dense film directly bears the impact (Up orientation), it does not participate in managing the impact during the initial stages of the impact as it simply moves like a rigid body with the indenter head, as compliant foam directly underneath relaxes instantly. Because of this, polyurea and polyurethane films are not engaged to dissipate the impact energy. The first deformation starts at the lowest point of the foam, which is in contact with the force plate as it is essentially stationary. For this reason, the stiffness and hence the force-time characteristic of the bilayer sample during the initial stages is controlled by the properties of the EVA foam and it is only near the peak of the force-time response that the dense polymer is activated and its effect becomes visible. Since polyurea is known to have superior damping properties compared with polyurethane [7,11,20–22], the reduction in the peak force in the polyurea samples compared with polyurethane samples in Figs. 2, 3, and 4 occurs while displaying almost *identical* response during the initial stages.

Now consider the Down orientation when the EVA foam is on top and directly hit by the indenter. As in the Up orientation, the foam starts to compress at its lowermost point away from the indenter as at that point its velocity is almost zero because it is resting against a very dense thin polymer film which in turn is supported above a steel force plate. The pressure at the dense film/EVA foam builds up immediately after impact and this activates an additional energy dissipation mechanism in the form of viscoelastic deformation inside the dense polymer layer. The combined effect of the EVA foam and dense polymer film is reflected in the sample displaying a higher dynamic stiffness immediately after impact as shown by the formation of a shoulder in the force-time response. Consequently, the peak impact force is significantly lowered as the total impulse is now redistributed more efficiently over

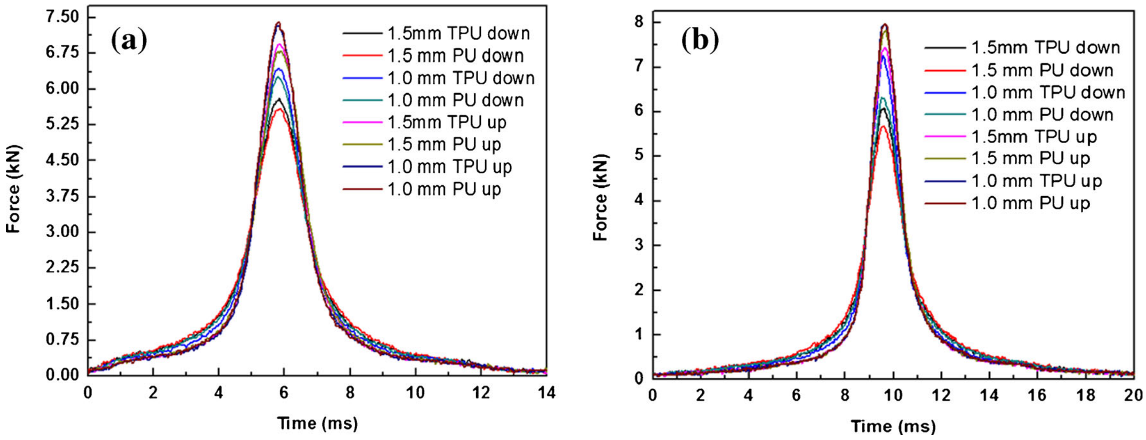


Fig. 4 Force-time history of (**a**) Type-A and (**b**) Type-B samples impacted by 7J energy (*TPU* thermoplastic polyurethane, *PU* polyurea)

Table 1 Summary of experimental results

Polymer film	Thickness	Orientation	Type A						Type B					
			3J		5J		7J		3J		5J		7J	
			Force (kN)	% reduction	Force (kN)	% reduction	Force (kN)	% reduction	Force (kN)	% reduction	Force (kN)	% reduction	Force (kN)	% reduction
Polyurea	1 (mm)	Up	1.68	23 %	4.19	22 %	7.39	15 %	1.56	39 %	4.72	38 %	7.97	21 %
		Down	1.3		3.28		6.27		0.95		2.93		6.32	
Polyurathane		Up	1.62	10 %	4.08	10 %	7.33	12 %	1.46	26 %	4.67	24 %	7.97	9 %
		Down	1.45		3.68		6.43		1.08		3.57		7.25	
Polyurea	1.5 (mm)	Up	1.58	23 %	4.05	30 %	6.80	18 %	1.5	39 %	4.37	46 %	7.81	28 %
		Down	1.22		2.85		5.60		0.91		2.37		5.65	
Polyurathane		Up	1.61	22 %	3.95	22 %	6.93	16 %	1.54	38 %	4.48	36 %	7.44	18 %
		Down	1.26		3.09		5.81		0.95		2.85		6.08	

time. Furthermore, one can see why the flipping effect is more pronounced for the lower density EVA foam. In the Down orientation the dense polymer film supports the weak EVA foam right from the beginning while it only engages marginally in the Up configuration as the lower density EVA has to undergo a substantial deformation before the dense polymer can be loaded. Specifically, the differences in the peak forces in the Up and Down orientations for the Type-B samples that utilize a lower density foam varies anywhere from 9 to 46 % which is much higher than those displayed by the Type-A samples (10–30 %) that use a higher density EVA foam. Specimens in the Down orientation display a higher dynamic stiffness, immediately after impact, as seen by the formation of a shoulder in the force-time response. The displacement of the top surface of the dense polymer film that contacts the indenter was estimated by directly integrating the force-time curve using the procedure outlined in ASTM Standard D 7136/D 7136M [23]. This is demonstrated using the force-time curves shown in Fig. 5 for pure foam and two bilayer samples made by bonding the same foam (high density EVA foam) with 1.5 mm thick layers of polyurea and polyurethane.

Another important aspect of our data in the down configuration is that the peak force is reduced while essentially maintaining the same impulse duration ***T***. The biomechanical injury criterion is dependent upon ***P***, ***T*** and ***1/t***. Human body can tolerate very high loads if ***T*** is very short (less than 10 ms), and as ***T*** is increased, body's non-injury force limit starts to reduce exponentially [17]. Thus, the ability of the bilayer system discussed here to reduce ***P*** without increasing ***T*** has significance in injury prevention and biomechanics.

Conclusions

This study is the first to report unusual observations of (1) dramatic differences in the peak dynamic force by just flipping

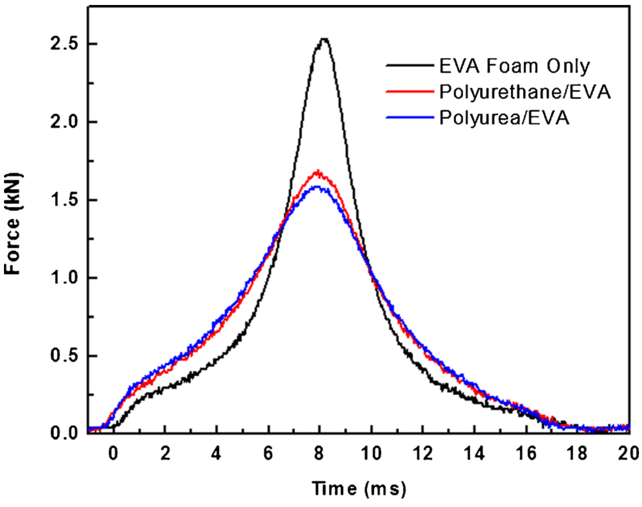


Fig. 5 Force-time history for samples impacted by 3J energy

the bilayer specimen in the low strain rate regime; (2) the said reduction being accompanied by higher dynamic stiffness and consequently lower overall specimen displacement; and (3) the peak force is reduced without significantly increasing the duration of the impulse. This should excite research leading to newer armor designs that are effective against dynamic loads with impulse duration in the 1–100 ms range. Since such impacts are ubiquitously encountered, results presented here have the potential to impact our daily lives in a significant way.

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