FLEXIBLE STAB RESISTANT CERAMIC-BASED BODY ARMOUR

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ABSTRACT

This paper presents the results of a study on performance of flexible stab resistant ceramic-based composite body armour that our research group has initiated, designed, assembled, and tested. The test outcomes were characterized in terms of the kinetic energy of the stabbing weapon at impact and the depth of penetration of the stab into the armour. A neutral date fitting model that departs from the classical least square approach is proposed. The test results show that the flexible panels are especially suitable for medium and low protection levels and by comparison with rigid panels, the flexible panels allow a deeper penetration which increases with thrust energy.

Keywords: body armour, stab-resistant, ceramics, composites, neutral data fitting

ARMURE FLEXIBLE DE PROTECTION CONTRE DES ARMES TRANCHANTES BASÉE SUR DES PLAQUES DE CÉRAMIQUE

RESUME

Cet article présente les résultats obtenus dans notre laboratoire sur la performance des panneaux flexible de protection contre des armes tranchantes, fabriqués en matériaux composites basés sur des plaques de céramique. Pour les paramètres étudiés, en utilisant l'approche statistique basée sur la régression neutre, on a trouvé que les panneaux flexibles sont particulièrement satisfaisants pour les niveaux de protection bas et moyens. La pénétration des armes tranchantes dans les panneaux flexibles est plus profonde que dans les panneaux rigides et elle devient plus forte avec l'augmentation de l'énergie cinétique.

Mots-clés: armure personnelle de protection, résistance contre des armes tranchantes, céramiques, matériaux composites, régression neutre

INTRODUCTION

Stab-resistant body armour is intended to provide a high level of protection against injuries that penetration of knife blades, spikes, edged blades, and sharp-pointed stabbing weapons may cause as well as to ensure that the movement of the wearer is not unduly restricted. Typically, existing stab resistant products rely on monolithic, front and back, solid plates inserted into protective vests to ensure coverage of the vital organs. These monolithic plates, while highly effective, have an inherent rigidity that limits comfort and restricts body movement. Ideally, a protective system should be light and flexible, yet should maintain the stab resistant characteristics of a rigid plate.

In our design, the armour core is a reticular array of small ceramic tiles. Three models of composite protective body panels in the flexible series have been manufactured in our laboratory to date, where the ceramic tiles, specially laced, are imbedded into a polyurethane matrix with a Kevlar® inner layer [1, 2]. This design allows the armour to be moulded to more comfortably fit and flex with the human torso. The performance of the best panel from the flexible group is compared with the performance of a particular panel that has the core with similar characteristics, selected from the rigid series that we have previously manufactured [3, 4] using the Ceramor® [5] system.

The testing was performed following the general guidelines of the NIJ, National Institute of Justice, in particular the NIJ Standard - 0115.00: Stab Resistance of Personal Body Armour [6] and the standards published by the PSDB, Police Scientific Development Branch. The NIJ standard [6] and the Police standard [7] specify the minimum requirements for a body armour designed to protect the torso against slash and stab threats, and also describe tests methodology for the assessment. Some significant aspects that led to the development of these standards along with a comprehensive review of data used to establish improvements in test methods are described in reference [9].

A stabbing weapon may strike with various kinetic energies at the time of its impact. In view of [6] and [7], two distinct protection classes of energy levels – denoted here by E1 and E2 respectively, with three protection levels (L1, L2, and L3) within each class – are the bases on which a protective armour is to be engineered.

Armour of the lowest protection level, L1, is intended for extended wear and is designed to be concealable and light-weight; armour of protection level L2 is designed to be incorporated into a general service garment, while armour of the highest protection level, L3, is designed to be suitable for high-risk environments. An armour meeting the L1, L2 or L3 requirement should withstand the thrust energy of the 85^{th}, 90^{th}, or 96^{th} percentile of the statistical test population, respectively. The body armour must ensure the shielding of all vital organs at every protection level.

For energy level E1, the maximum allowed depth of penetration of a stabbing blade beyond the body armour is 7 mm. The test protocol requires additionally an over-test condition where the kinetic thrust energy E1 is increased by 50%. At this higher energy level, E2, the maximum allowed penetration is 20 mm. The over-tests are required to ensure that the design provides an adequate margin of safety [6 - 9].

Table 1 refers to the testing of stabbing weapons with edged blades providing the required kinetic energy at impact for various protection levels with the corresponding maximum allowable depth of penetration beyond body armour.

Protection Class	Protection Level	Energy E1 (Joules)	Allowable Depth Penetration	Energy E2 (Joules)	Allowable Depth Penetration
Edged Blades	L1	24 ± 0.5	7 mm	36 ± 0.6	20 mm
	L2	33 ± 0.6	7 mm	50 ± 0.7	20 mm
	L3	43 ± 0.6	7 mm	65 ± 0.8	20 mm

Table 1 Kinetic energies at impact and the maximum allowed depth penetration of a stabbing blade at various protection levels

EXPERIMENTS

The engineered knife blade P1/A which is the stabbing weapon used in our experiments was selected for its aggressiveness and also to ensure consistency of both the geometry and the material properties of the blade throughout testing. The knife blade P1/A is mounted in a sabot (Fig. 1) that is provided with a Plastazote® closed cell foam damping system. The total mass of the sabot, including the blade holder and the damping system, is 1.84 kg. The impact angle was set at 0° incidence to replicate the most severe situations. The assembly is well centred and balanced.

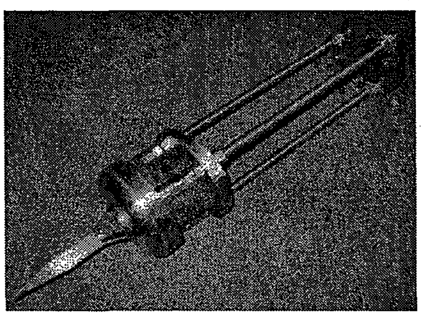


Fig. 1 Drop mass with P1/A knife blade

Protective Panels: Design and Manufacture

Two series of stab resistant ceramic-based composite body armour, F-flexible and R-rigid, with three and six models of protective panels respectively, have been designed and manufactured by our research group to date. The armour core in these models is a reticular close-packed array of small, thin, light-weight ceramic platelets. The platelets are alumina-based ceramic tiles chosen for their relatively low density, high fracture toughness, high material strength*,

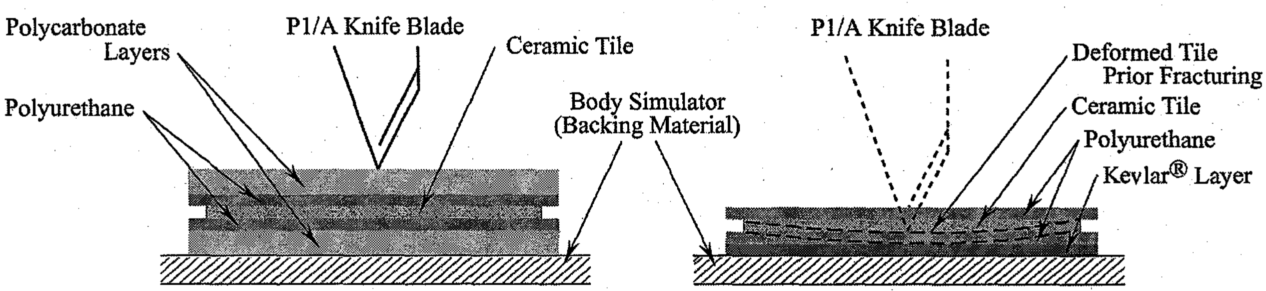
* The manufacturer [5] provided the following data: density of 4,000 kg/m^3; ultimate compressive strength 1,920 MPa; ultimate tensile strength 340 MPa; Poisson's ratio 0.21; elastic modulus 337 GPa; percentage of elongation at fracture 0.6 %, and fracture toughness of 7.2 MPa m$^{1/2}$.

as well as for their ballistic multi-impact capability when properly confined within polycarbonate layers using polyurethane as adhesive. The selected tiles are square-shaped measuring 43.2 mm by 43.2 mm and the chosen thickness may vary from panel to panel. The tiles are manufactured by Aceram Technology Inc. of Kingston, Ontario, Canada [5].

In the R-series, the ceramic tiles are sandwiched symmetrically between polyurethane and polycarbonate layers (Fig. 2-a) known as the Ceramor® system [5]. The polyurethane layer acts mainly as an adhesive. Despite the good overall performance, the system proved to be rigid and uncomfortable to wear.

To achieve a certain degree of flexibility, we have designed the F-series. In order to significantly reduce the flexural moment of inertia, the polycarbonate layers have been eliminated thus, the ceramic tiles are kept in place by the polyurethane matrix alone (Fig. 2-b).

The panels have been manufactured using a cylindrically shaped aluminium mandrel with central rise of 25 mm over a span of 350 mm, to replicate the chest of a male.



(a) Rigid Panels with Polycarbonate and Polyurethane Confinement (b) Flexible Panels with Polyurethane Confinement

Fig. 2 Support system with and without polycarbonate confinement

The protective panel would become flexible if line joints could be formed in the array between the rows of the tiles, the flexibility of the line joints corresponding to that of the polyurethane matrix. To maintain, however, proper alignment and spacing of the array during the manufacturing process is rather challenging. We have developed a special technique to ensure proper alignment and uniform spacing and, ultimately, panel flexibility. Prior to installing the tiles, a grid of strong cotton thread is laced tightly. The thread is laced through sequences of holes accurately placed in the mandrel. The holes are aligned in such a way that when the ceramic tiles are placed in each square of the grid, their edges are flush with the lacing thread. By using this technique, the panels become flexible along every line of the square grid formed by the line joints. The spacing between tiles is minimal; it is wide as the thickness of the thread used for the lacing, which typically is 1 mm.

The composite assemblies of ceramic tiles are further vacuum bagged and cured either under pressure in the temperature-controlled autoclave* (Fig. 3) or in a temperature-controlled oven.

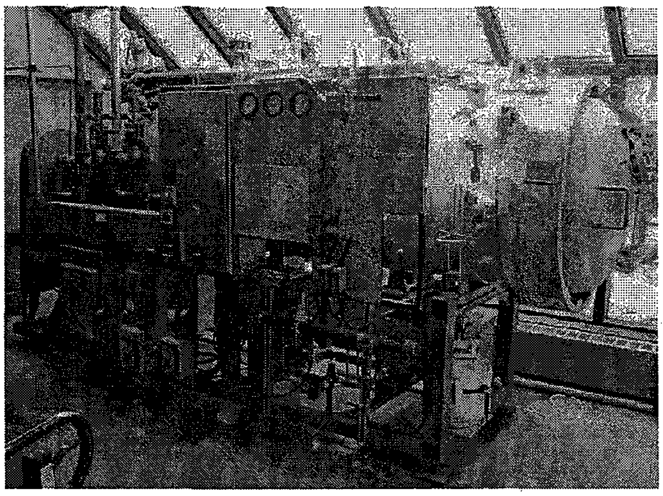
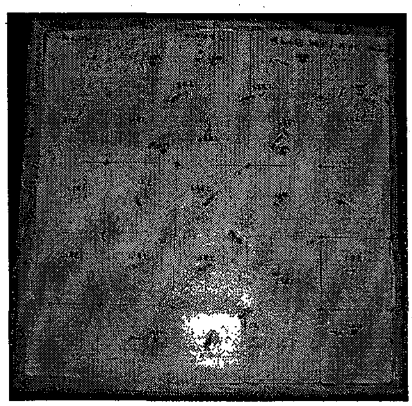


Fig. 3 Royal Military College research autoclave

In developing the different models of protective panels, we have tried various materials, tile thicknesses, and curing parameters. Panel F3 (Fig. 4-a) turned out to be the best outcome yet from the flexible group. Its performance is compared with that of the panel R2 from the rigid series (Fig. 4-b) which features tiles of the same ceramic type and thickness as the ones used for panel F3. Both panels F3 and R2 have been tested under the same conditions, using the same apparatus and the same techniques.

(a) Flexible panel F3



(b) Rigid panel R2

Fig. 4 Flexible and rigid panels after testing

Our current objectives include gaining insight on the performance of the newly developed flexible body armours and defining directions for further research and development.

* The RMC research autoclave provides a cylindrical working volume of 0.80 m in diameter and 2.40 m length, and it is capable of curing composite materials to temperatures up to 200° C and pressures up to 1.02 MPa (10 atmosphere)

Test Apparatus

The test apparatus is shown in Fig. 5. It features a vertical tube 5.2 m long with a square cross-section of 100 mm by 100 mm. The weapon, i.e. the sabot holding the P1/A knife blade, falls through the tube and at the end impacts the panel.

It was determined experimentally that the cylindrical sabot, once stabilized at the height chosen for a particular test, travels freely down the tube without acquiring any rotation during its free fall. The weapon can be dropped from various predetermined heights to strike the panel with the desired kinetic energy.

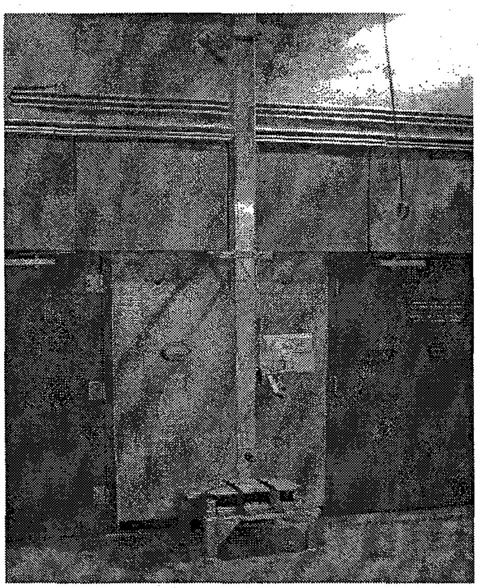


Fig. 5 Drop test apparatus

The lifting device consists primarily of a fibreglass surveyor's tape, a hand winch, and an electromagnet. The electromagnet works as a permanent magnet unless a voltage is applied. In the event of an accidental power loss, it will not release the weapon.

The protective panel to be tested is placed over a stack of special materials that simulate the human torso [6,7]. The stack consists of, from top to bottom, four layers of RA110 neoprene sponge, each 5.8 mm thick, a single layer of Plastazote® closed cell foam, 31 mm thick, and two layers of 2494D natural rubber, each 6.5 mm thick.

The panel and the stack of materials are strapped together securely to a wooden crate. The whole assembly is laid on a sturdy aluminium table and placed under the drop tube for testing.

The kinetic energy of the stabbing weapon at the time the blade impacts the panel is determined with the relation $E=mgh=\frac{1}{2}mv^2$ where m is the drop mass, g is the acceleration of gravity, h is the drop height, and v is the velocity at impact. The velocity is determined using two sensors placed at the bottom of the drop tube, close together, on the same vertical line. A trigger occurs each time a metal surface of the drop mass passes by a sensor. The difference in time registered by the two sensors is marked by an oscilloscope, namely, Nicolet 420 12 bit PRO with a sensitivity of 0.01 ms.

The penetration depth of the knife blade through the protective panels has been measured as the distance that the tip of the blade protrudes from the rear of the body armour.

TEST RESULTS AND CONCLUSIONS

Ceramic-based flexible body armour panels have been successfully designed, assembled, and tested in our laboratory. A total of 34 drop tests have been carried out on panels F3 and R2. Some tiles were stabbed more than once. Although microfractures developed, no visible bridge-fractures occurred in the rigid panel, owing to the good confinement provided by the polycarbonate layers; in the in the flexible panel, however, visible radiating fractures did occur.

Of significant interest is determining how the panels compare, over a range of data, in regard to the blade penetration depth when the weapon stabs the panels with the same kinetic energy. The tests were performed at the highest impact energy levels, E2, over a range of values of kinetic energy that includes all protection levels, L1, L2, and L3. The results are plotted in Fig. 6, where the kinetic energy of the stabbing weapon at impact is taken on the x-axes, and the depth of penetration of the blade, on the y-axis.

Ceramic tiles present an inherent high variability through manufacture and this is reflected in the spread of the distribution of results, for each position level.

In the flexible panel F3 the ceramic tiles were confined only by polyurethane as seen in Fig. 2-b, thus lacking the strong confinement and reinforcement provided by the additional polycarbonate in the rigid panel R2 (Fig. 2-a). As a result, panel F3 bent severely under the high force of impact at the highest energy level setting, cracking and allowing a deeper knife penetration. Nevertheless, the lateral gouging and friction between the steel blade and the ceramic fragments still held in place and confined by the polyurethane, prevented the knife blade from advancing further.

The depth of penetration of the stab into the armour increases with the kinetic energy of the stabbing weapon at impact. As a first approximation and also from physical reasoning, we consider a linear model.

One of the most widely used methods for fitting of a function to data is by means of least squares criterion. The conventional or the ordinary least square method consists in minimizing the sum of the square of the y (vertical) deviations from the data points to the fitting line. The method imposes an underlying assumption that x, the independent variable, does not have natural and/ or measurement error. If the technique is applied to the interchanged dependent-independent variables, then the same set of data will generally produce a different linear model.

We would like to draw the attention to the neutral data fitting that departs from the conventional or the ordinary least squares approach, allowing natural variation and/ or measurement error in both variables. It is named neutral data fitting as no variable is given a special treatment. The method has appeared under different names in various disciplines and this may have played a part in not being more widely known. In astronomy it is known as Stromberg's impartial line, in biology it is the line of organic correlation, and in economics it is known as the method of diagonal regression. It is noteworthy that the method of neutral data fitting has attracted the attention of most distinguished researchers, with Nobel laureates such as Paul Samuelson and Ragnar Frisch having published work on it [10].

In two dimensions, the neutral data fitting method considers the sum of the absolute values of the product of deviations in the x- and in the y- direction from each data point to the fitting line,

$$F(\beta_0, \beta_1) = \sum_{i=1}^{n} |(y_i - y)(x_i - x)|,$$

where $y = \beta_1 x + \beta_0$, (x_i, y_i) is the data point in the i^{th} observation, and n is the number of observations. The estimating parameters, i.e. the slope of the fitting line and the y-intercept, are those values of β_1 and β_0 respectively that minimize the function F. There is always one, and only one pair of such values.

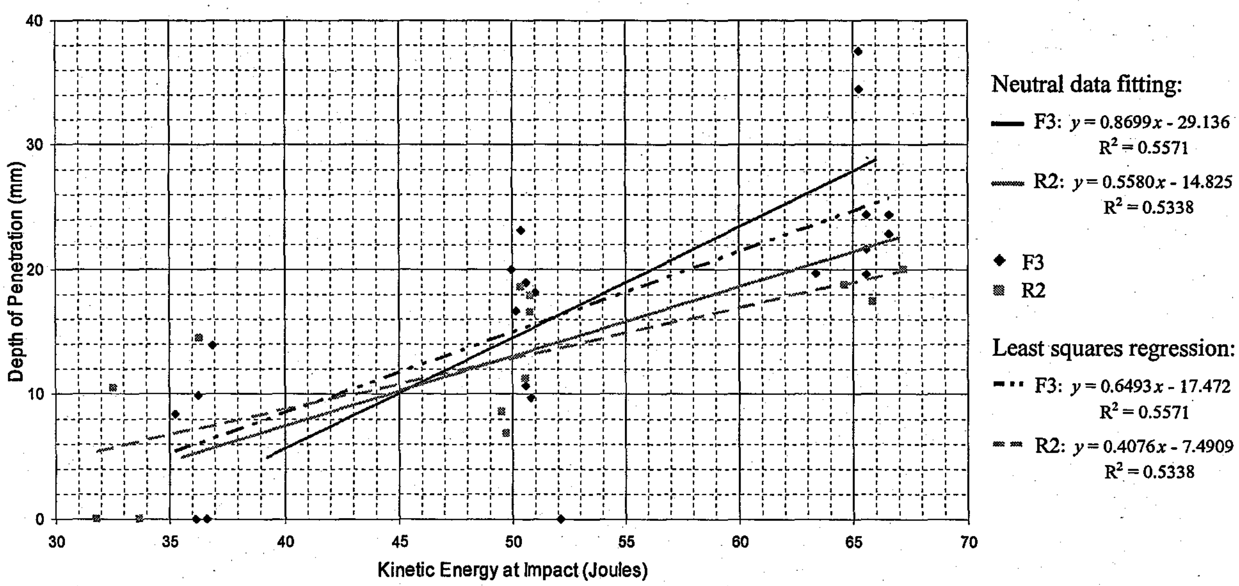


Fig. 6 Experimental results for protective panels F3 and R2

The method produces the same model irrespective of which y is regressed on x or x is regressed on y. The emerging line has remarkable geometric and invariance properties. In particular, it is invariant under scale change (which is not true for some other procedures, notably for the total least squares regression), and invariant under linear transformations of individual variables. The line of the neutral data will be lying always somewhere between the two extremes provided by the ordinary least squares lines y regressed on x (denoted in Fig. 6 by dotted lines) and x regressed on y (not shown).

To conclude, the tests results suggest that over the range of interest of parameters investigated, for the same kinetic energy at impact, the depth of penetration of the stabbing blade into the flexible panel is grater than into the rigid panel, and that the difference gradually increases as the kinetic energy at impact increases. The flexible model F3 is proven to be suitable for medium and hence also for the low protection level, whereas the rigid model R2 could be used in all protection levels environments.

Future research and development will include consideration of alternative designs and curing parameters and of utilizing also some other materials for the core and confinement layers, to ultimately achieve a higher degree of flexibility, higher degree of protection, and cost effectiveness.

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