RISK FACTOR ANALYSIS ON FIRE FIGHTER’S POSTURE WITH SCUTUM-SHAPED SHIELD INCLUDING LOAD AND THERMAL EXERTION

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Abstract. Great evolution of armours went on and this led to progressive development and improvement on the design of shield, for example shields used by law enforcements. However, a flexible shield for firefighting purpose is yet to be designed and developed. The suitability of interaction between the shield and user also remained questionable. The objective of this paper is to propose a conceptual design of a shield for fire resisting purpose, considering the ergonomics factors and behavior under load exertion. The methodology used are customer survey, house of quality, morphological chart, pugh method, rula-analysis, and simulation using finite element analysis. Scutum-shaped shield has been selected with aluminium alloy 6061-T6 as the inner body material of shield, and is wrapped by the standard elastic modulus type carbon fiber. The final score of 3 in RULA analysis indicated the shield possess only low risk of Musculoskeletal Disorder. Under load exertion, von mises stress of shield reach 320Mpa once load of more than 8kN is given to the shield.

Keywords. Firefighting Purpose Shield; Rula-Analysis; Load and Thermal Exertion

1.0 INTRODUCTION

Armors have been developed to accommodate the increasing and ever-changing methods of inflicting harm [1]. Shields were usually reliable defense for infantrymen and knights before plate armor became a
commonplace form of guard. Various types of material, either metal or non-metal like wood, had been used in crafting shields. Soldiers who can afford only low price shields used to combine thick sheets of wood with paste and tanned leather to create a durable aegis. However, it differed from iron-made-shields which simply dent under blows from weapons, wood-crafted-shields tend to crack and fall apart if they were suffered from heavy impact. Investigation on suitable material in the making of shield has grown progressively, while more and more lightweight, yet high strength material are made possible for shields of different purposes, such as riot shields [2], ballistic shields [3] and military shields [4].

Development of shields focused not only on its crafting material or composition, but on the ergonomic factor as well. For instance, the straps located behind the blocking part of shield were reshaped for better control over blocking. A handle or strap would be grasped by hand, and the secondary strap would fit over arm. This enables soldiers to put the power of their weight behind blocks and attacks. This finding is supported by Czarnecki & Janowitz [5] that modern body armour is more comfortable and flexible than ever. Unlike the past where shields were made by combination of several material, shields had been made monolithic, usually of high hardness steel, but yet they are too unwieldy to be carried. Thus, the demands to have lightweight shields for personal protections led to the study and discovery of alternative materials in crafting shields. Non-metallic materials, such as ceramics and composites, have been progressively incorporated into more efficient lightweight armours [6].

2.0 RESEARCH METHOD
The project was initiated by conducting customer survey to define firefighter’s needs. The feedback received was generally in terms of material, shape, weight, dimension, function, strength, and manufacturing cost. These customer needs were translated into quantifiable engineering characteristics. Next, morphological approach was used to divide the overall design problem into simpler sub problems. Solution concepts are generated for each sub problem defined. The next step is to generate all designs by synthesizing possible combinations of alternatives for each sub problem. The design concepts generated were undergone Pugh selection method to evaluate, and to choose the best concept design [7]. Lastly, the suitability and comfort of the interaction between manikin and shield were analyzed using RULA analysis. This analysis was also done to examine work posture suitability at welding workstation [8]. Finite Element Analysis (FEA) was performed to simulate the behavior of shield under load and thermal exertion. The overall research method is illustrated by Figure 1.

3.0 RESULTS AND DISCUSSIONS
A survey questionnaire was prepared to acquire fire fighter’s response on the characteristics and specifications of the design of fire resistance shield. The survey consists of a total of 15 questions relating the necessary information needed in designing the shield such as age, height, experience in firefighting cases, movement during ceasefire, shape of shield, dimension, additional necessary features, weight, strength and affordable price. 50 respondents were involved in this survey and they are the firemen stated in Malaysia. The data obtained varies from individuals with different experiences
and it depends on their personal points of view. About 92% of the respondents have experienced more than 10 fire cases, proving that most of the respondents approached are senior firemen and they have wide experiences in fire rescue. In terms of shape, 72% of the respondents preferred scutum-shaped while oval and lozenge are not favorable as they are more likely result in poor human factors. Based on the experiences and knowledge of the firemen, carbon fiber has been chosen as the most suitable material by about 56% of the respondents due to its high melting points and relatively lightweight. The result of survey serves as the basis on designing a fire resistance shield that fulfils firemen’s requirements, which is then fed into House of Quality (HoQ) as shown by Figure 2. HOQ helped to identify the engineering characteristics that are the most important in fulfilling the customer requirements. A total of seven customer requirements on the design specification of fire resistance shield have been identified and their feedback on each criteria.
Figure 2. House of Quality

has been translated into quantifiable engineering characteristics. According to the results, it is found that upgrading the tensile strength is most important for improving firefighter satisfaction with shield quality and the installation of added features is least important. If the budget is sufficient to complete all recommendations, the problem will become very trivial. The lightweight and suitable dimensions of shield size are also important since bringing heavyweight accessories will produce discomfort and tense to the muscle. A further analysis is necessary to select which recommendations should be completed. Table 1 shows the morphological chart of shield organizing the possible solutions for each parameter. This morphological chart allows the idea generation on the following conceptual design. Conceptual design is the result of synthesizing the more possible combinations of possible solution for each parameter. Five possible combinations of sub problem solution identified are generated from the morphological chart as shown by Figure 3. By using Pugh concept selection method, the five possible combinations of sub problem solutions can be compared qualitatively in every single alternative to a datum alternative. The result of qualitative comparison is shown in the Table 2. The shield design alternative 2 and 4 are superior to the reference/datum. Alternative 2 was chosen to be the design for further development since it ranks the highest in advantages over the datum, with manufacturing cost factor prior to be considered. The shield design alternative 2 developed with Aluminum Alloy 6061-T6 as the core material. With weight, strength of material, manufacturing cost and susceptibility to corrosion as the dominant factors to consider in the selection of suitable core material, Aluminum Alloy 6061-T6 fits comparatively well over the other types of material studied in literature review.
Table 1. Morphological Chart of Shield

| No. | Parameter                      | Possible Solutions          |
|-----|--------------------------------|----------------------------|
| 1   | Inner body (core) material     | Aluminium Alloy, Silicon Carbide, Carbon Fiber |
| 2   | Direction of handles aligned   | Horizontal, Vertical, Slanting |
| 3   | Handles raw material           | Aluminium Alloy, Silicon Carbide, Polymer |
| 4   | Core material wrapping         | Carbon Fiber, Polymer, Spray Coating |
| 5   | Ergonomics Concepts            | Malaysian people, American people, European people |

Figure 3. Generated Concepts

Table 2. Pugh Decision Matrix for Shield Design
The Aluminum Alloy 6061-T6 as the core material is to be wrapped with carbon fiber of standard elastic modulus type (HT) to resist it from high heat temperature which may cause it to deform, as well as a protective layer for shield to prevent it from corrosion or rusting. Carbon fiber has superb melting point and strength over the metals, however, the manufacturing cost of shield solely using carbon fiber is too high to afford. Hence, the carbon fiber is to be used as wrapping to the core material, and the standard elastic modulus type (HT) carbon fiber is selected as it possess sufficient high melting point and strength to withstand high heat and impact forces in case of fire emergency. Figure 4 shows the parametric design of fire resistance shield in millimeter scale. The height and width of shield is given by 500 mm and 400 mm respectively. The shield is designed to be curved inward with the shape of eclipse, and with the height of curvature equal to 70 mm. The thickness of the shield is designed to be 5 mm. The shield is configured with two handles aligned horizontally. Handle 1 is made of adjustable strap for more flexible, secure and comfort fastening around the right arm. Handle 2 on the other hand, is made of fixed and rigid metal to be grasped by right hand. In the center of shield embedded with a spotlight which will be protected by wire netting to protect it from damage when it is in impact with striking objects.

![Figure 4: Scutum-Shaped Shield](image-url)
Further, RULA analysis has been performed with manikin in both standing and kneeling positions as shown by Figure 5 and Figure 6 below in order to examine the suitability between manikin and shield at different positions. It was chosen because the working posture in this study mainly involved the movement of upper parts of human body [9]. Based on interviews, firefighters experienced discomfort at lower back, hips, elbow, thighs and ankle. They also complained that the weight of the shield must be maximum about 3.5 kilograms to avoid overweight in performing repetitive work task. The final score of the analysis with a value of 3 obtained shows the kneeling down position while carrying the shield is ergonomic with low risk level of Musculoskeletal Disorder (MSD). However, further improvement can be made in order to prevent negative cases that will effect firefighter’s health and safety. From the observation, the main causes of posture problems are the uncomfortable pole, awkward postures due to holding of the shield and the repetitive work. They caused muscle and nerves discomfort to the firefighters specifically at wrist and arms when tasks were being repeated for a long period of time. Compare to the work done by Deros et al. [10], the score for holding shield is better since working movement of the harvesters affects mostly on the upper part of their body where task is performed higher than the elbow level.

![Figure 5. Rula-Analysis in Standing Position](image-url)
The linear static properties of the designed fire resistance shield is simulated by using Solid Thinking Inspire software. The shield is simulated for its effect under different load exertion, and also its thermal behaviour under heat. Displacement results are initiated for both normal mode and linear static analyses. It is a vital factor to consider for general analysis to recognize the deformation of a structure, fire resistance shield in this case, for the loads applied. For the simulation of load exertion on shield, the displacement parameter is targeted to achieve 2 mm of displacement as an indication of shield surface deflation that can be detected through naked eyes. The von Mises stress is commonly used as parameter to define the structural performance of ductile materials. When the von Mises stress reaches up to the yield stress of the material of a structure, the material has started to undergo yielding, and this phenomenon is often referred to as failure of structure. The typical yield strength of Aluminium Alloy 6061-T6 is found to be around 320 MPa. The shield structure is considered to fail when the value of von Mises stress is greater than 320 MPa as shown by Table 3. Based on the table, the shield experiences a displacement of 2 mm upon acted under load of $6 \times 10^5$ N. Under the exertion of load up to $8 \times 10^5$ N, the maximum von Mises Stress achieved is about 316 MPa. Since the yield strength of Aluminium Alloy 6061-T6 studied is 320 MPa, the shield structure is expected to deform or fail at the load exertion of above $8 \times 10^5$ N.

**Table 3. Load vs Displacement vs Von Mises Stress**
Figure 7. Temperature vs Displacement

Based on the figure 7, the deformation of carbon fiber is negligible even under high temperature of 1,000 °C. This is because carbon fiber possesses high melting point that it can be said to have fire resistance property. From the interview, the predicted temperature during a fire is in between 600°C and 800°C. On the other hand, the shield design can be further improve using topology [11] and topography [12] optimization.

4.0 CONCLUSIONS

A survey questionnaire was prepared to acquire fire fighter’s response on the characteristics Thermal resistance, impact strength and weight are the most important criteria in the design and development of a fire resistance shield. Aluminum alloy 6061-T6 has been selected as the body material and was wrapped with carbon fiber to further resist the shield from deforming under high temperature, as well as a protection layer from corrosion. Aluminum alloy is lightweight and yet relatively high strength. In terms of ergonomics based on RULA analysis done in both standing and kneeling position, the final score was 3 which indicated the shield possess only low risk of musculoskeletal disorder (MSD) and it can still be improved. For Finite Element Analysis (FEA), the shield experienced a displacement of 2 mm upon acted under load of 6 ×105 N. The shield will only deform at load above 8000N. Since the shield is wrapped
with carbon fiber, it is literally fire resistance as the displacement of shield simulated under temperature up to 1000°C is negligible.

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