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ANALYSIS OF FLEXIBLE BARRIERS USED AS SAFETY PROTECTION IN WOODWORKING

Abstract: *Machine tools use physical barriers, made by flexible thermoplastic materials, to protect the environment and the operators against the projections of wood chips and parts of cutting tools. These barriers constitute a partial closure and allow the passage of the workpiece, being simultaneously able to contain sharp fragments projected at high speed. The present research was conducted with the aim to evaluate the real effectiveness of these barriers, to investigate their dynamic behaviour by numerical simulations. Results showed that these barriers, if properly considered, could retain heavier masses and higher speeds. The research also allowed, in fact, to investigate the influence of several factors in design, selection and use, as material, shape, position, assemblages and many others, highlighting weaknesses and identifying possible measures to increase its effectiveness.*

Keywords: *flexible barrier, aramid fibers, projection of tool parts, safety in woodworking*

1. Introduction[1]

Machine tools do not pay special attentions to people during woodworking: they act cutting wood and ejecting fast slivers in every direction (Figure 1). Many operators discovered this reality in unfortunate circumstances. Machines with moving parts and workers who operate them have an uneasy relationship. Machines make workers more productive and enable them to form and shape material in ways that would be impossible with hand tools. Technology can make machines safer, but as long as workers need machines to help them process material, they will be exposed to moving components or ejecting parts that could harm them. Much of the danger occurs at the point of operation, where the work is performed and where the machine cuts, shears or drills. Anyway, according to Procter, (2015), most machine-related accidents involve operators loading or unloading components, removing swarf, taking measurements or making adjustments (as in the case of coolant supply). On manually operated machines, the moving tool typically injures operators. Automatic and CNC machines also present hazards through movement of machine elements. Injuries range from minor cuts and abrasions through to eye injuries,

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broken bones, dislocations and amputations (fingers and hands are not infrequently lost). Fatalities can also occur, often arising from hair or loose clothing becoming entangled with moving machinery.

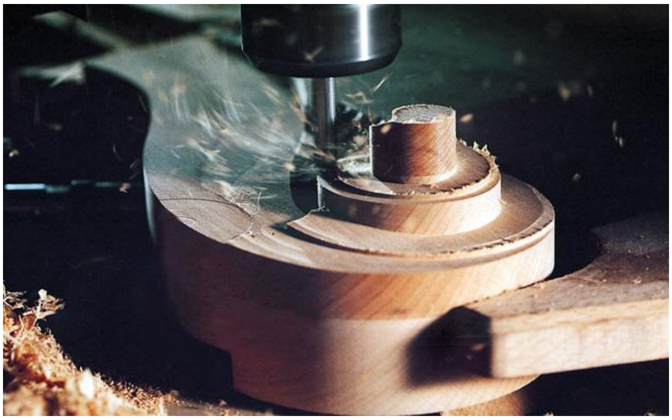


Figure 1. Production of chips during woodworking

In 2011, the *US National Electronic Injury Surveillance System* database published statistics concerning injuries related to wood shop machinery in the United States. These results were largely spread thanks to the investigation by *Consumer Product Safety Commission* (details in CPSC, 2011). It was highlighted that the number of accidents in US (in 2007-08) was incredibly high, between 80.000 to 100.000 cases per year. Many of these incidents can be prevented by means of fixed guards (Figure 2), often in conjunction with jigs and fixtures (to make loading and unloading of components safer), and safe means of setting up, removing swarf, taking measurements and making adjustments. It is noteworthy that these measures can either prevent access to dangerous parts or prevent access until such time as the parts are no longer dangerous (e.g. on machinery that has a run-down time).

Figure 2. Use of rigid barriers in wood processing (Procter, 2015)

Most of the modern devices are oriented to effectively safeguard at the point of operation. They can include the presence of sensing devices, two-hand controls or trips, gates or restraints. For instance, the presence of sensing devices creates an invisible sensing field and permits to catch working parts entering the hazard area and either prevent a machine cycle or stop the hazardous motion of the machine. These devices represent an excellent method of safeguarding because they do not create a physical barrier between the operator and the operation zone, allowing a complete visibility of the working area. Adding they can easily be "blanked" to allow material movements, permitting a regular manufacturing (ANSI, Hamelund 2012; Gavazzi, 2012; WorkSafe, 2006). At the same time, the use of these "active" solutions in woodworking is sometime rather complex and uncommon considering that the technology they are based on, is often expensive and delicate. For instance, dust can easily blind sensors. Moreover, these devices, primarily designed for safeguarding against accidental introduction of objects (including hands) in the working area, are not developed to protect against the ejection of projectiles. On the contrary, in machines for woodworking an important safety issue to be deal with is exactly related to the risk of expulsion, during processing, of wooden chips, metallic fragments (as blades) and, even, not correctly fixed tools. This extreme phenomenon can occur when a cutting tool is not correctly positioned in its seat or, furthermore, when not properly balanced. Instability leads to dynamic vibrations and unplanned levels of stress in tools up to a final break with the consequential ejection of parts. More frequently safety problems in woodworking occur when heavy wooden chips or, even, tool fragments break during processing. It is noteworthy that nowadays a cutting tool for an efficient woodworking consists in a complex system made by a large number of diamonds blades, thermally welded on a hard steel core (Figure 3).

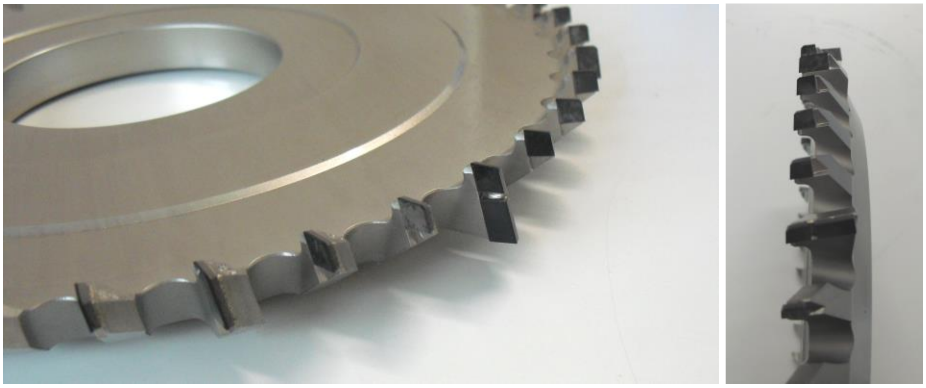


Figure 3. A tool for squaring: diamonded inserts on a steel body (Courtesy Hogger)

Progressive material degradation, violent impacts against wood, extreme thermal stresses, excess in vibrations, un appropriated welding process are some of the most common reasons providing favourable conditions for rupture and ejections (by the spindle rotation) of fragments of tools.

In this case, an extremely rigid barrier could represent the best solutions (Figure 2). However, it is not always possible to equip the working machines with rigid protections, dimensioned in the way to retain these fast projectiles. Mass and speed, in fact, may be such as to achieve very high kinetic energies and, at the same time, a robust, and generally unmovable, barrier could represent an obstacle for a fast production: an inacceptable side effect. As a consequence, in the recent years, design solutions moved toward the general scope of reducing the risk *at source* as much as possible, in the way of saving the productivity. In line with this concept, a particular attention was paid to the realization of safer tools, with, for instance, the adoption of advanced auto-balanced fixing systems (UNI 847-1, 1997; UNI 847-2, 2001). More generally, over the past twenty-five years, several important researches were carried out on the reliability and safety of tools for woodworking, achieving remarkable advances in safety (Lucisano *et al*., 2016; Fragassa *et al*., 2016; Fu *et al*., 2008; Cheeseman and Bogetti 2003).

In the recent years, a notable advance in safeguarding regarded the introduction of concepts and materials quite similar to ones used in the realisation of bulletproof vests and protections. In a modern ballistic defence, instead of a single shield, extremely rigid and robust, a multilayers level of protections is preferred. Usually it is realized using very strong, but flexible fibers (e.g. Kevlar), able to catch and deviate the bullet in multiple inelastic impacts, spreading its energy over a larger portion of the barrier. In the case of machine tools, a flexible protection can consist, in practice, in several layers of flexible curtains, made by an impact-resistant material, where, in each layer, several curtains are located side by side (Figure 4). This kind of barriers, surrounding the working area, can represent a valid solution in protection of workers from the ejection of fast projectiles. In fact, the projectile, attempting to cross the barrier, would impact against these flexible layers, progressively losing kinetic energy, up to remaining trapped in not-dangerous areas. At the same time, respects to other protective solutions, flexible barriers seem to offer a valid compromise between factors such as: efficiency in protection, complexity in design, appropriate cost, durability and maintainability. Consequently, flexible curtains have been increasingly their attractiveness between machine tools' manufactures. Their utilization is subordinated to an accurate analysis of benefits, balanced by a factual validation of the level of protection offered. Several investigations moved in that direction (Myrcha *et al*. 2000; Lucisano *et al.* 2016; Prokter 2015).

Figure 4. Use of flexible barriers in wood processing

2. Regulation

Studies realized on flexible barriers, together with analogues studies on rigid ones, were considered as basis for developing of specific standards on safety in woodworking.

Generally, it is possible to state that, in the case of machines that use tools made in accordance with those standards (e.g. dimensions) and until requirements provided by the same standards are respected regarding the operation conditions (e.g. speeds), it can reasonably considered as negligible the risk due to parts' expulsion.

Specifically, the standard EN 848-3, is addressed to take carefully into consideration all these safety aspects in the case of drilling machines and CNC milling machines. It introduces technical requirements at minimizing the risk of tool breakage and projection of it parts against the operator by means of reducing the probability of:

- an over speed of tools;
- an incorrect programming of the working cycle, in order to prevent the use of inaccurate parameters that could cause a tool impact against the rigid parts and possible damages;
- an incorrect choice of tools

In particular, regarding this last aspect, a clear definition of the technical characteristics to be observed for the selection of the appropriate cutting tool, in the case of milling cutters and circular blades are reported in EN 847-1 and EN 847-2.

The EN 848-3 also provides, as residual risk, the possibility that small pieces, such as sharp fragments, escape and are projected into the environment at normal cutting speeds (UNI 848-3, 2004). To reduce this risk the installation of flexible barrier, made in thermoplastic materials: polyamide, polyurethane, polyvinyl chloride or similar material with equal resistance, were suggested.

As reported in several investigations (Wang *et al.*, 1998; Wang *et al.*, 2004), the effectiveness of flexible barriers depends on their behaviour under dynamic conditions and can be related to several parameters (as material used, number of layers, etc.). In particular, the phenomena of impact are totally different from what happens in rigid barriers, where the ability to retain a mass depends almost exclusively on the mechanical resistance of the material. Adding, the practical experience has demonstrated that flexible protections are also able to retain and trap effectiveness small fragments (Williams and Vaziri, 2001; Yun-jie, 2010). The standard aimed at regulating the size and shape of these barriers based on the experience acquired during their use.

Till today there is no evidence of incidents of machines manufactured in accordance with EN 848-3, used in accordance with manufacturer's instructions (UNI EN 848-3, 2004). However, the effectiveness of these barriers was contested by one of the country members of the European Community and this has led to consequent depth technical analysis. In several expert meetings organized by the Commission, it was actually recognized that the effectiveness of these barriers is not proven, at that time, by any systematic research conducted by qualified bodies, and how the solutions found by the standard were mainly stated by the good sense of the regulators based on experience gained in similar applications. Since then several research or standard organizations have been involved in the development of safety regulations related to machine for woodworking (Lucisano *et al.*, 2016). Improvements have been made, by verifying experimentally the capability of barriers made by flexible thermoplastic material to retain small tool parts during the normal cutting velocity.

In particular, in 2008 the standard EN 848-3 was completed by defining a comprehensive and rigorous procedure for the experimental verification of the efficiency of the protective barriers (UNI EN 848-3, 2004). This procedure was established as a useful guide for manufacturers of machine tools for woodworking. However, this rule is rigid enough not allowing taking full advantage of the rapid evolution in the materials and techniques of construction of barriers, rather worrying to freeze certain solutions. The results provided in different experimental campaigns (Pera *et al.*, 2014), still have not permitted to evaluate the effectiveness of barriers which realization deviates significantly from the configuration currently widespread and preferred by the standard (UNI EN 848-3, 2004). At the same time, research continues to verify the convenience of configurations and/or assemblies other than those most common ones, also considering the use of new materials that allow obtaining a higher efficiency. This effort toward new solutions is related to the general desire of reducing the high costs of current protective barriers, and, at the same time, to increased efficiency, lightness and functionality.

3. Objectives and methods

3.1 General aims

This research deals with the effectiveness of flexible barriers, used in woodworking during drilling or milling by CNC machines, respect to the ballistic impacts. In particular the barriers under investigation were realized overlapping single curtains, side by side and layer after layers. Each curtain consisted in a slight fabric made by aramid fibers, Kevlar or polyester rather than PVC. In some cases, curtains were also coated, by PVC or polyurethane, with the aim to improve their resistance against scratches (Field and Sun 1990; Duan *et al.*, 2002). The behaviour of the barrier respect to these non-linear dynamic impacts was investigated by FEM simulations (AUTODYNA, 1997; LS-Pre post, 2012). Regarding the projectile, it was considered in relation to its mass, shape, speed and its direction striking against the barrier. Regarding the curtains, several factors that affect the ability to retain the projectile were identified. The knowledge of these factors represents a fundamental aspect for "designing" an effective barrier and, in particular, for the correct selection of: material, shape, number of layers, position, etc. of curtains. Different choices are possible in relation to the specific characteristics of the machine tools and processing.

Adding, during the research, procedures and practical tricks were developed for taking fully advantages of all the potentialities of FEM codes respect to the simulation and analysis of the largest variety of impact conditions. Machines, tools and barriers were initially imagined in correspondence with the requirements from EN 848-3, but a large number of different conditions, not covered by the standard, were also investigated. Accordingly, it was possible to identify the limits of applicability of the barrier (in term of safety efficiency) in relation to changes in projectiles' and barriers' parameters. Understanding the influence of these factors is an essential task with the scope to design an effective protection and, in particular, to permits the coherent choice of curtains' material, shape, number, position, constraint conditions, etc. Technical information has to be also related to the specific peculiarities of the machine tool and the working process. In line with this scope, as relevant additional result, a practical proposal of methodology was formulated, to be utilized as an integration of the current EN 848-3, in design and evaluation of the effectiveness of "uncommon" protections for woodworking machine tools.

3.2. Analysis of regulations and their limitations

In EN 848-3, as said, an experimental test to validate the effectiveness of the barriers using standardized test equipment is proposed. In this case, the projectile consists in a steel bullet, of conical shape, *20g* of mass, impacting at *70m/s*. Several other possibilities exist in standards, but this combination was preferred since it better represents real impacts in woodworking. The examination of common accidents involving tools confirms, in fact, that the projected parts weight around *12-14 g*.

The barrier contains curtains with the width between *40mm* and *60mm* and, at least, three overlapped layers. The arrangement of barriers has to represent the actual operation of the barrier. The projectile is shouted from *250mm* of distance and must hit the barriers in the middle of the strip. The distance of the shot is considered as representative as the risk situation effective in the area of the machine tool. The barrier is considered adequate if the bullet remains caught in its interior or, at least, falls at a distance not more than *400mm*. When the standard was released, this limit was considered adequate to protect the operator from being injured also considering his distance from the equipment. Unfortunately, more and more often it is in the presence of special tools with heavier parts or machines working at very high cutting speeds. As a consequence, in the recent years, an addendum to the standard was attempted to address the problem by changing some parts of the experimental verification and, in particular, increasing the mass of the projectile prudently to *100g*.

This change can be considered more like a *prudential practical suggestion for manufacturers* rather than an accurate evaluation of the impact phenomenon. In fact, due to the complexity of the energy/dynamic phenomena, it has never been arrived to determine a mathematical correlation between a particular type of barriers and the value of kinetic energy that it is able to retain. In practice, there is no way to evaluate in advance the effectiveness of barriers which implementation is significantly different from the most common configurations. And, as a consequence, each new barrier has to be validated using the expensive EN 848-3 tests.

This is precisely the limit against which this research moved. Overcoming the current experimental approach, it provided an appropriate tool to numerically evaluate the efficiency of any kind of protective barrier. Consequently, it is possible seeking for a more effective protection by the use of different barriers (geometry and materials) or innovative assemblies (for configurations, overlays, etc.). However it is also possible to extend these security checks to machine tools and processes that do not precisely correspond to the standards (e.g. faster machining).

3.2 Technical specifications

Before starting with the Finite Elements (FE) modelling, it was necessary to carry out a preliminary analysis to identify the fundamental parameters and define an appropriate scheme of simulations. In very general terms, these technical parameters can be mainly related to the:

- mass, speed and shape of projectile
- position of impact into the barrier, but also the directions of motion
- size and geometry of the individual curtains
- weight of curtains and other material characteristics
- size and geometry of the entire flexible barriers
- external effects such as friction and fixing system

Referring to the projectile, the bullet was defined, as much as possible, in accordance with a sense of reality. Technical literature and also practical experiences highlight that tools that often provoke projection of small parts or fragments are those with cutting edges connected to the body with a permanent fixing (Pervan *et al.*, 2015; brazing, welding, etc.) or complex tools (Figure 5a) where cutting inserts and blades are mounted on the body with detachable fasteners (Figure 5b).

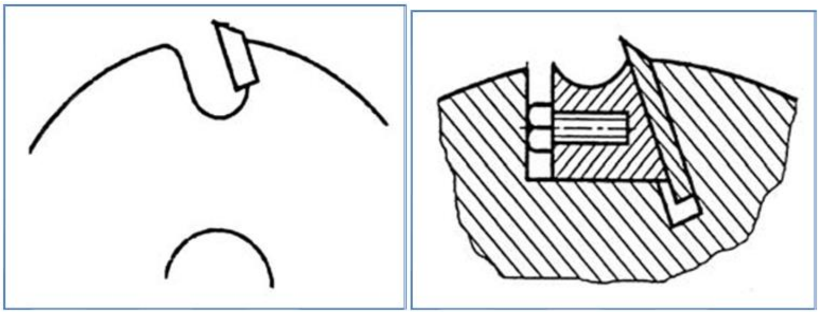


Figure 5. Complexity of tools for woodworking processes

Since it is not easy to anticipate the specific shape of a potential bullet in such complex situation, it was evaluated the effects of different shapes. In particular, the cylindrical head with a conical square footprint, as proposed in standards (Figure 6), was compared with a conical frustum, but also simpler geometries as a sphere and a cylinder.

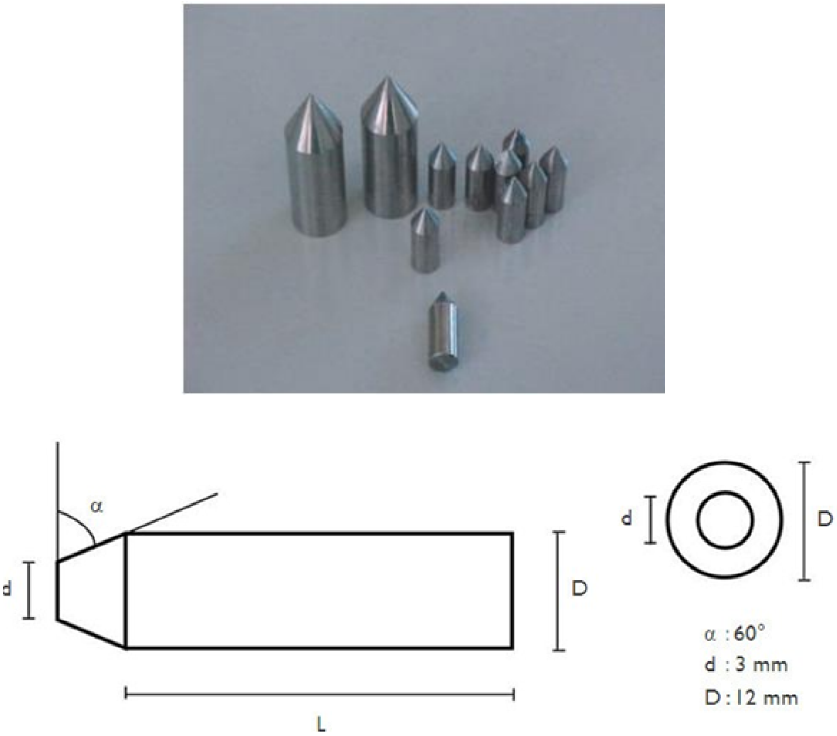


Figure 6. Standardized projectiles for ballistic tests (EN 848-3)

Weights from *20g* to *100g* were investigated with the aim at being in line with the past and recent version on EN 848-3. With regard to the speed, indications provided by EN 848-3 were also considered, using the referenced value of *70m/s*. This value was considered as highly representative of the real speed of projectiles ejected from the working area by peripheral rotation of tools in the case of woodworking, usually around *50m/s* and rarely up to *70m/s*.

A preliminary indication of size, shape and material of the barriers was also obtained by the same standard. Regarding the material, EN 848-3 rules that the barriers have to be realized in polyamide (PA), polypropylene (PP), polyurethane (PU), poly-vinychloride (PVC) or similar materials with comparable mechanical properties. Respecting to this assignment, the FE investigation was implemented considering different materials for curtains, among those most used by manufacturers. In Table 1, these materials are listed, together with their main mechanical characteristics. In this way, the research also permitted to compare these different fabrics, relating their efficiency in protection to their material characteristics. Fabrics made by polyesters or aliphatic polyamides (Nylon) or aromatic polyamide (Kevlar) and PVC were used. Some fabrics were coated with PVC or polyurethane with the aim at improving the resistance to abrasion and the durability in general. They were characterized by specific physical-mechanical properties such as density, tensile strength and modulus of elasticity, strain at break, which are important for the behaviour of the barrier respect to impacts (ATP, Mehler, Tecnodam, Kevlar, Zivkovic *et al.*, 2016).

Table 1. Mechanical Characteristics of Kevlar and Nylon (*Peox* and *Matrix*)

		Kevlar	Peox	Matrix	Method
Weight	g/mq	280	687	867	ISO 3801
Resistance to abrasion	cycles	>50000	>50000	>50000	ISO 12947
Tear Force	N	351-355	479-612	536-374	ISO 13937
Tensile Strength	N	3039-3066	3016-3007	3006-3007	ISO 13934
Elongation at break	%	12	24-25	23-24	100mm

Always according to the EN 848-3, one protective barrier has to consist in, at least, two overlapped layers, having a height not exceeding *400mm* and a total thickness not less than *10mm*. Each layer consists of a series of vertical curtains of a width not less than *40mm* and not more than *60mm*, dynamically independent one from the other. In this research it was carefully investigated the benefit related to an improvement in the number of layers, for 1 to 16 layers (Figure 7).

With aim to correctly define its size, including the number of layers, it is important to identify which part of the barrier is really relevant for the impact. It has to be notice that only curtains moving when hit directly by the bullet or indirectly by the strips set into motion by the impact have effect in protecting. If a curtain is involved or not, depends on its position in the barrier (and, consequently, on the specific configuration of the barrier), but also on the location of impact. In fact, the projectile can generally impact in any points: in this FE analysis, several cases were investigated as impacts at three different heights (*40mm* below the clamping point, at the center, *40mm* above the edge bottom), and also choosing between an impact at the center of a single curtains or between two bordering curtains.

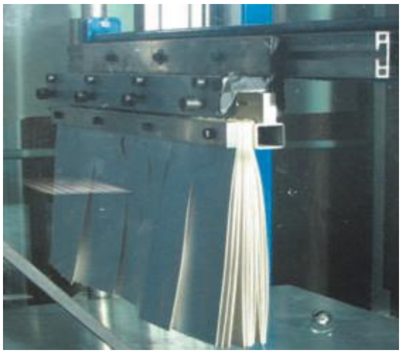


Figure 7. Barriers with16-layers

Considering the high speed, a period of time up to *200ms* was observed. In general the mechanism by which the projectile is slowed down, in addition to the loss of energy by collision and friction, is dominated by a phenomenon of the catch of the part of the strips of the material in motion. After the impact, the projectile remains trapped between the flexible strips. This capture is facilitated by the flexibility of the material. Figure 8 clarifies this process.

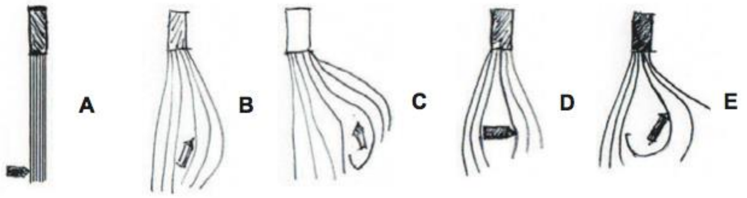


Figure 8. Sequences of capture of the projectile (Pera *et al.*, 2014)

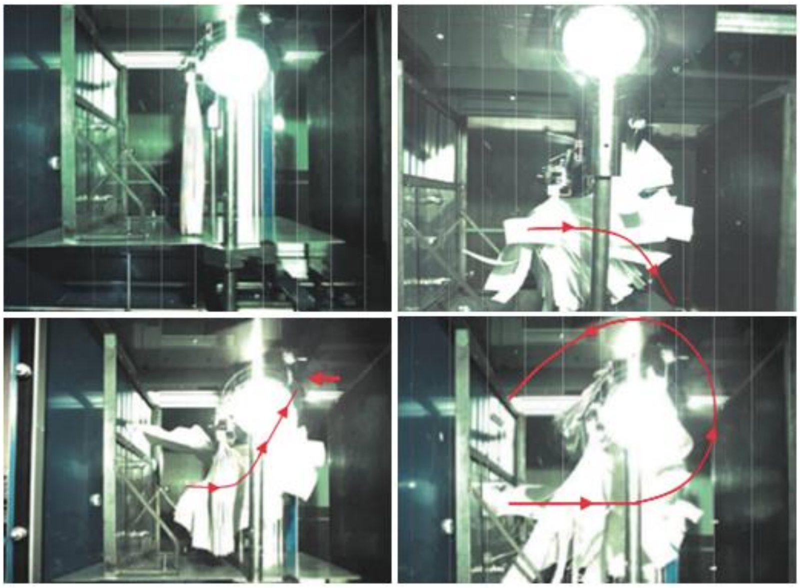


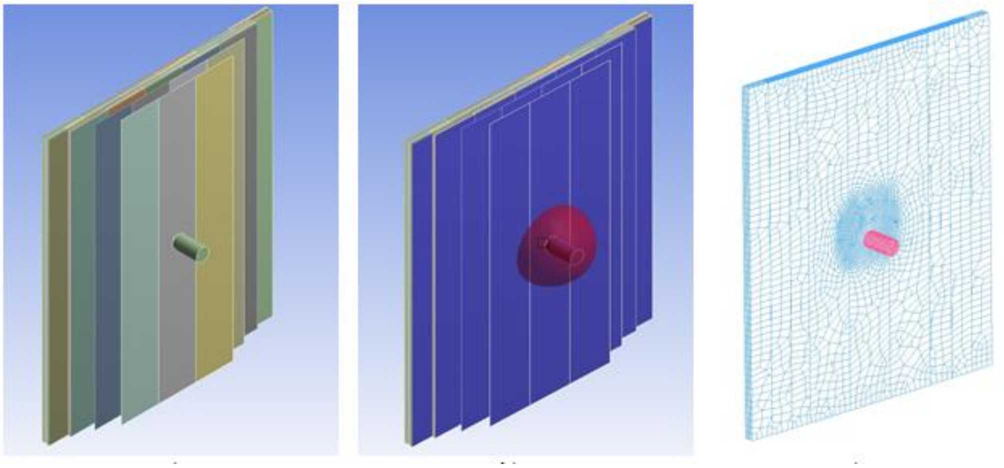
Figure 9. Difference sequences of capture of the projectile (Pera *et al.*, 2014)

Moreover, it is noteworthy that the efficiency of the barrier has to be considered not only in terms of its ability to trap the bullet, but also to deviate the projectile toward safe zones. This concept is extremely important. In fact, in the larger part of practical cases, the barrier cannot be dimensioned to completely absorb the huge kinetic energy charactering the fast impacting bullets. This is the physical condition necessary for trapping them inside the barrier. However it is not even necessary. For assuring the external protection, it would be enough to deviate the bullet back or against the rigid frame of the machine tool. And it could be much easier, also because it is possible to benefit of the effects of the multiples impacts occurring to the bullet inside the barrier. Figure 9 reports difference sequences of capture: the specific modality of capture depends on the particular configuration of the barriers.

4. Numerical analysis

4.1. System discretisation

Beyond the specificities of each situation, as preliminary phase in the numerical investigation, a common process of discretizing of the whole system (bullet + guard) by nodes and elements had to be implemented. Figure 10a reports this sequel, passing from geometry to FE model. In particular, a sphere of influence was carefully defined on the impact zone (Figure 10b), with the aim at refining the mesh in the area of contact (Figure 10c). FEM simulations were realized combining *Ansys Workbench* and *LS Dyna* codes.



a) b) c)

Figure 10. Finite Element discretisation of the impact

In Figure 11, additional details about the process of discretisation by Finite Elements are reported. In particular, it is possible to perceive the stratification of FEs applied in the case of layers creating the curtains (Figure 11a), but also the refining of geometry by smaller elements, closer to the impact zone (Figure 11b).

The sensitivity of results to changes in discretizing parameters were also investigated with respect to:

- mesh type, size and number of elements, the number of nodes
- time step calculation

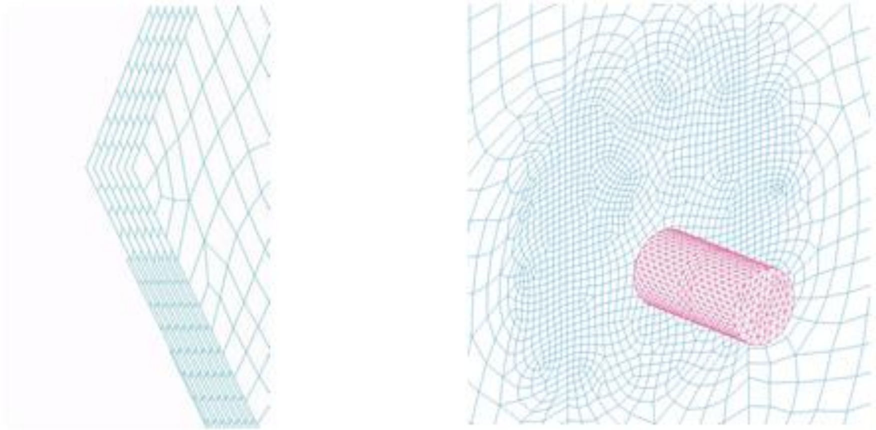


Figure 11. Details of discretisation: layers and impact zone

The dynamic of impact was investigated and efficiency compared observing, in particular:

- trajectory of the bullet during and after the collision
- projectile's release distance and time
- speed of the projectile with respect to the axis of motion
- residual kinetic energy of the bullet
- changes in the kinetic energy of the barrier
- changes in the internal deformation energy of the barrier
- stress and strain variation in the curtains.

It was also verified the conditions of energy and total system motion conservations.

4.2. Crossing the guard

In Figure 12 the dynamic of the impact against a *three-layer* barrier, investigated by FEM, is reported as example. It represents the simplified case of a standard bullet impacting, orthogonally and exactly in the center of the barrier. This sequence can be conveniently used to represent the different steps of the physical phenomenon and to introduce several technical details of simulation.

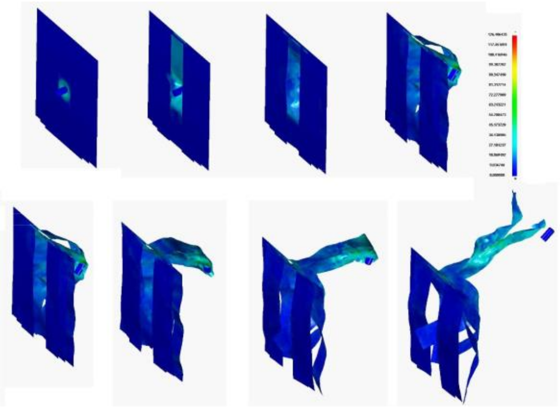


Figure 12. Impact modelling, contact phases, crossing and releasing the projectile

Initially the bullet strikes against the curtain located on the first layer. A lump of its flexible surface is quickly created with the aim at absorbing the pressure. The level of stress rapidly increases, together with the material deformation. Then, the curtain starts to move folding: the lower border, free to move (respect to the upper one, fixed on the frame), starts to lift. This upward movement, making the curtain to pass away respect to the impact point, permits to reduce the level of local stress. At the same time, the curtain is pushed ahead, against the curtains located on the second layer. The curtain is insinuated as a wedge, in between the other curtains and their movement starts. In this way and by other secondary impacts, the initially kinetic energy is transferred from the projectile to the whole barrier. After less than an instant, the bullet passed the barrier, but curtains continues to be weaved together, obstructing the projectile's trajectory. Finally the bullet is released, but with a kinetic energy and direction that largely reduce the risk of damages. In the case of wider barriers (>8 layers) the projectile struggles to exit.

4.3. Physical correspondences

The way a single curtain reacts following the impact of a bullet is displayed in Figure 13. When undeformed fibers are hit by a projectile, they are deformed and start to move. In the case of multiple layers, each curtain in motion immediately hurts against others, creating a complex effect. In this case, only a FEM simulation allows investigating the complex phenomenon (Gower *et al.*, 2008). Figure 14 shows what happens when a fast projectile impacts and crosses through a multi-layer barrier. A good correspondence between the theoretical model of impact on a single layer and the numerical reconstruction of this impact against multi layers barrier is evident.

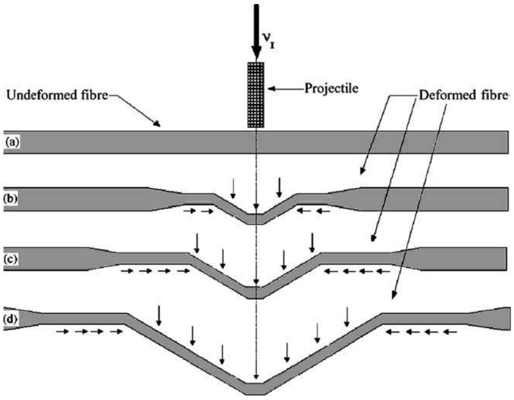


Figure 13. Model of impact

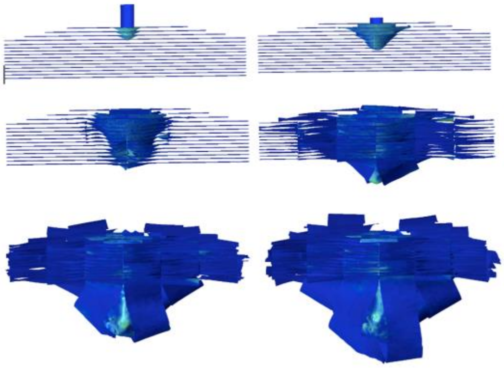


Figure 14. Crossing a multi-layer barrier

Adding, there are experimental evidences over the barriers laying on the bottom, in the way to offer a wide bend towards the tool, both in the concave and convex part, to simulate the behaviour of the barriers when resting on the work piece. The behaviour of the barriers backed showing the concave part towards the tool is more effective than that of the suspended barriers. The resting barriers for which the tool is located on the convex side, when hit in the bottom, they offer an invitation to lift the strips of the barriers, so that a smaller resistance projectiles, which are not relevant, especially when compared with the same strips affected in the lower part of their height. In any case, the standardized test configuration provides that the barrier in vertical position is not touching any surface. The phenomenon is accentuated as the length of the strips and is characterized by a clear swelling of the whole assembly, within which the projectile dissipates its energy. For this reason, for example, *400mm* curtains provide higher performance than *200mm* ones. This result was also evident in FE simulation. As regards to the width of single curtains, a certain improvement in performance was also noticed with larger dimensions, as in the case of *80mm*. It is probably due to the fact that the wider strips offer more possibilities, either to capturing the projectile or disperse kinetic energy rearranging themselves after the collision.

5. Results

5.1. System analysis

A large number of simulations were implemented and compared, starting from the simplest one, as a single rectangular curtain, fixed on the top and orthogonally hit in the center, to a complex one, with 16 layers in friction, curtains with trapezoidal shape, an locally increased weight, transversally hit at the border, exactly between two adjacent strips.

In line with the details technical specifications, the following variable were considered:

- properties of material used for curtains
- height, thinness, width and shape of each strip
- number of layers
- overlap configuration and distance between layers
- constraint and friction conditions

These simulations permitted to investigated how the efficiency of the barrier is influenced by aspects as: boundary conditions, improvement in weight, curtain’ shape, material proprieties, etc.. In particular, Figure 15 reports the efficiency of barrier respect to improvements in weight (Figure 15a) or boundary height position (Figure 15b) of the strip. While heavy materials positively and directly impact on the level of protection offered, as easily anticipated by considerations on the inertial masses, the height of the barrier does not act in a proportional way, but through geometrical considerations, as previously detailed.

Also changes in the mechanical properties of materials were investigated (Figure 15c) demonstrating that changes around 8-10% in the efficiency of protection are possible even with.

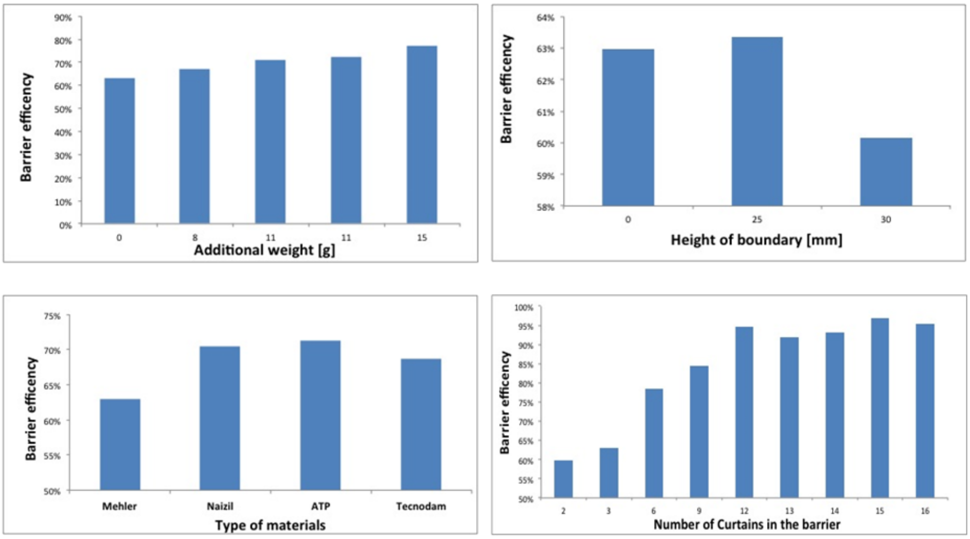


Figure 15. Efficiency of barrier respect to: a) weight, b) height of the strip; c) material; d) number of layers.

The effect of the number of layers was finally analysed (Figure 15d). Referring to this last, but very relevant aspect, as general confirmation of a common experience, 14 layers were evaluated as the minimum stratification of curtains necessary for an adequate protection in woodworking.

5.2. Impact phenomena

According to the FE simulations, the bullet loses large part of its kinetic energy in very few impacts, transferring this energy to two or three initial layers; however, from closer examination it turns out that the decrease of energy is greater when the impact occurs against the wider barriers, not only because a larger mass is involved in the collision as target, but also because the energy is quickly spread on a major surface and, then, uniformly distributed between curtains. Even the presence of an increasing number of layers, with the same thickness, has a positive effect on the reduction of speed, thanks to the higher number of consecutive impacts to which the projectile is subjected. It is consequently verified that it is better to use a higher number of layers in the way to split the impact by little inelastic collisions: the energy is not preserved, but dispersed in forms as heat, vibration and sound energy. By a comparison between maximal stress and ultimate stress, it is also verified that the projectile cannot under any circumstances perforate the curtain, even if it can cause significant damage to the surface, especially at high speeds and for higher masses. The prevalent effect of the impact is to move and lift the barriers, possibly passing through the gaps that are created due to the confused movement of the impacted barriers. The integrity of barriers is preserved by its high flexibility. Even in the extraordinary case of a bullet perforating the curtain, it tends toward be blocked inside the same strip as in a bungee cord: surprisingly, the apparently dangerous phenomenon of perforation of barrier has a positive effect on safety. It is not a coincidence, in fact, that the initial experience in the use of flexible barriers, showed the ability to retain small fragments of tools, as they were found stuck in the same barriers. This result may indicate a new way of barriers construction, choosing softer materials for the penetrating barrier part that is facing with the tools and harder one outside. Unfortunately, the barriers are continuously in contact with the work piece and, if they were too soft, they would remain damaged in a short time.

Correspondingly it happens that the ability of the barrier to retain the projectile increases as much as the same hit near the clamping line. This occur because closer is the hit point to the fixing system the more the barriers behave in a rigid way. For the same reason, probably, the effectiveness of the shorter barriers is not reduced; even they are characterized by a smaller mass due to the smaller height of the barrier. Also in this case the explanation has to be found in the increased stiffness due to the shorter distance of the points of impact from the fixing system, and then to the lower flexibility of the barriers further favoured by their lower height. It should be noted, however, that the variation of the barrier effectiveness, as that the points of impact move away from the clamping line, does not follow a linear behaviour. Probably when the collision occurs, producing in that way a chaotic movement of the barriers emerges open gates, which can facilitate the passage of the bullet. Such gaps become wider in the lower part of the barriers where their displacement is larger, highlighting the phenomenon. Following all the considerations made so far regarding the positive effects due to the barriers stiffness, it should be remembered that the stiffness and hardness of the material of which they are made should not be such as to scratch or damage the wood.

The logic makes it obvious that the projectiles that hit the vertical carving between barriers pass more easily that, at the same height, crash into the solid part of the strip, however it is clear how the differences are not sensitive. This is probably due to the fact that, even if the braking effect due to the crossing of the first layer, taking place through the slit between two strips, is reduced, the number of test strips set in motion is greater. As it regards the positioning of the strips, the fact that they directly affect the normal operation has a positive influence on their effectiveness.

5.3 Toward a synthesis

The protective behaviour of the barriers can be summarized in:

- Effectiveness of the barriers increases as the point of impact approaches the constraint
- Effectiveness of the barriers does not decrease with the reduction of the height, despite the lower mass concerned to the phenomenon
- Effectiveness increases in barriers with wider strips
- Effectiveness increases in barriers which, for a total thickness, are formed by more layers; deformability of the first hit layer has a strong influence on the phenomenon
- Bullet does not pass for perforation of all layers of the barrier: even if arrived to perforate the first layer, it cannot pass through since it remains catch in the strips
- Bullet passes only in the case when strips lift up.

There is a negligible difference in behaviour between the bullet hitting the center of the strip and the one that hits the separation line between two strips. Combining this kind of information to those coming from the state of the international art, it was possible to reach important general conclusions such as:

- Evaluate the relative weight of those parameters that influence the behaviour of the barriers, some of which have already been identified in theory or experimental
- Restrict the mass range and speed of real interest in the way to guide a following tests, from which it can be attended quantitative results
- Define a simulation model suitable for the validation of the barriers in full agreement with EN 848-3, for those cases in which it applies

4. Conclusions

During woodworking, physical barriers protect the environment and the operators against the projections of wood chips and parts of cutting tools. At the same time, the barriers have to allow the rapid passage of the work-piece. This compromise is assured by flexible barriers, which represent a design solution not fully standardized. This investigation was realized with the aim at evaluating the real effectiveness of these barriers, investigating their dynamic behaviour by numerical simulations. Results showed that these barriers, if properly considered, could retain heavier masses and higher speeds. The research also investigated the influence of several factors in design, selection and use, as material, shape, position, assemblages and many others, highlighting weaknesses and identifying possible measures to increase its effectiveness. In particular, as first step, FEM simulations adopted all parameters suggested by standard with the aim at completing a validation analysis of these hypotheses. Then, additional cases were selected between those of largest interest for practical applications. By the simulations, opposite of what happens during experimental tests, it was possible to analyse the complex behaviour of a flexible protections hit by the bullets and, in particular, the configuration that the various barriers assume in space and time. It was also possible to identify the trajectory of the projectiles before and after the collision with the barriers, evaluating speed and loss of energy. These results are crucial for understanding the physical phenomena behind the multiple impacts and for the correct evaluation of the effectiveness of the barriers.

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References:

AUTODYNA (1997). *Interactive non-linear dynamic analysis software*, Horsam, UK. Century Dynamic.

Cheeseman, B.A., & Bogetti, T.A. (2003). Ballistic impact into fabric and compliant composite laminates. *Composite Structures*, *61*, 161-173.

Duan, Y., Keefe, M., Bogetti, T.A., & Cheeseman, B.A. (2002). Modelling the impact behaviour of high-strength fabric structures. *Proceedings of the Fiber Society Annual Technical Conference*, Natick, Massachusetts.

Field, J.E., & Sun, Q.A. (1990). High speed photographic study of impact on fibres and woven fabrics. *The Proceeding of the 19th International Congress on High-Speed Photography and Photonics - Part 2*, 703–12.

Fragassa, C., Zigulic, R., & Pavlovic, A. (2016). A Practical Guideline for the Design and Use of Tools in Woodworking. *Tehnicki Vjesnik, 23*.

Fu, S.C., Zhang, X.Q., & Chen, G.Y. (2008). The reasons analysis and prevention for working accidents of common woodworking machinery. *Wood Processing Machinery, 2*, 003.

Gavazzi Automation Components (Ed.) (2012). *Technology for safety – Safety Light Barriers, Safety Mats, Safety Modules.* Gavazzi Automation Components (Ed.), Canada. Retrieved from: https://www.gavazzionline.com/pdf/SafetyBrochure.pdf

Gower, H.L., Cronin, D.S., & Plumtree, A. (2008). Ballistic impact response of laminated composite panels. *International Journal of Impact Engineering, 35(9)*: 1000-1008.

Green Cover, Tessuti Spalmati, Naizil S.p.

Hamelund, C. (2012). *Machine Safeguarding at the Point of Operation - A Guide for Finding Solutions to Machine Hazards.* Oregon OSHA Standards and Technical Resources (Ed.). Retrieved from: http://www.cbs.state.or.us/osha/pdf/pubs/2980.pdf

LS–PrePost Online Documentation. Extended Tutorials. Retrieved from: http://www.lstc.com/lspp/content/tutorials.shtml Livermore Software Technology Corporation (2012).

Lucisano, G., Stefanovic, M., & Fragassa, C. (2016). Advanced Design Solutions for High-Precision Woodworking Machines. *International Journal for Quality research, 10*(1), 143-158.

Myrcha, K., Wrobel, J., & Gierasimiuk, J. (2000). Data bases with hazardous situations in woodworking machinery design. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *44*(27), 352-355.

Pera F, Pireddu A, Betti I, *et al.* (2014). Cortine flessibili per fora-fresatrici da legno a controllo numerico. *Materiali e configurazioni innovative*. 1st ed. INAIL. Milano.

Pervan, N., Mesic, E., Colic, M., & Avdic, V. (2015). Stiffness Analysis of the Sarafix External Fixator based on Stainless Steel and Composite Material, *TEM Journal*, *4*(4), 366-372.

Prokter Machine Guarding. (2015). A Guide to Guarding Small Machine Tool Used in Machine Workshops (3rd Edition). Retrieved from: http://www.machinesafety.co.uk/

Prokter Machine Guarding. (2015). Guide to Machinery Guarding Standards. 10th Ed. Retrieved from: http://www.machinesafety.co.uk/

Savoia, M., Stefanovic, M., Fragassa, C. (2016). Merging Technical Competences and Human Resources with the Aim at Contributing to Transform the Adriatic Area in Stable Hub for a Sustainable Technological Development. *International Journal of Quality Research; 10*(1), 1-16.

UNI EN 847-1:1997. Tools for woodworking - Safety requirements - Part 1: Milling tools and circular saw blades.

UNI EN 847-2:2001. Tools for woodworking - Safety requirements - Part 2: Requirements for the shank of shank mounted milling tools.

UNI EN 848-3:2004. Safety of woodworking machines - One-side moulding machines with rotating tool - Part 3: Numerical control (NC) boring machines and routing machines.

Wang, D.L., Li, W.B., & Zhang, S.B. (2004). Study on accident endangering of woodworking machinery and the measures to safety protection. *Wood Processing Machinery*, *5*, 45-48.

Wang, Y., & Xia, Y. (1998). The effects of strain rate on the mechanical behaviour of Kevlar fibre bundles: an experimental and theoretical study. *Composites, Part A*, *29A*, 1411–5.

Williams, K.V., & Vaziri R. (2001). Application of a damage mechanics model for predicting the impact response of composite materials. *Computers & Structures*, *79*(10), 997-1011.

Work Safe BC (2006). Safeguarding Machinery and Equipment, General Requirements, SBN 0-7726-5588-X.

Yun-jie, X.U. (2010). Ergonomics-based Analysis of Industrial Accidents in Woodworking Operation. *Forestry Machinery & Woodworking Equipment, 11*, 010.

Zivkovic, I., Pavlovic, A., & Fragassa, C. (2016). Improvements In Wood Thermoplastic Matrix Composite Materials Properties by Physical and Chemical Treatments. *International Journal for Quality research*, *10*(1), 205-218.

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