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Development of Next Generation Column Guard - Final Phase of a Multi-Year Senior Capstone Project

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Abstract:

This paper presents the results of a real-world design project involving both undergraduate engineering and business students. The project involves the design, development, and prototyping of a next generation pallet rack column guard. The guard allows for the engagement and protection of a storage rack upright (column) from an impact force by an external object such as a forklift. The guard protects the storage rack by absorbing and damping the resulting impact force. The guard is constructed from an injection-molded thermoset elastomer. Elastomers can store and release more potential energy per unit mass (or volume) than steel and plastic guards. This translates to greater energy absorption which will help preserve the structural integrity of a rack upon impact thus protecting the general public in retail (big box) stores and warehouses. The final phase includes impact testing and developing a sales and marketing strategy – a collaborative effort between engineering students and the school of business. The results are presented in detail with emphasis on how engineering and business students collaborate.

1. Introduction:

This paper reports on a four-year, industry-sponsored design project involving the design and development of a column guard used to protect storage racks from forklift impacts. The project was used to support five separate undergraduate senior (capstone) projects spanning a time-period of approximately four years and involving sixteen mechanical engineering students and three business students. Early project work (year one and two) has been documented in previous publications [1 – 3]. Reference [2] presents a detailed summary of work completed for years one and two. This work included design and prototyping of various column guards, the design and fabrication of an impact tester, stiffness testing and benchmark testing. The current paper presents the final phase of the project which involved a group of four mechanical engineering students collaborating with a group of three business students. The engineering students were responsible for the final design and test validation while the business students focused on the marketing and business plan as well as customer interaction. The groups of engineering students interacted directly with the business students, holding weekly meetings. Customer visits and surveys arranged by the business team provided crucial information that the engineering team utilized to finalize the design. The final column guard is currently being field-tested at various warehouse and manufacturing plant locations throughout the region. Finally, the group of engineering and business students created a **product launch** strategy and planned roadmap outlining the steps and tactics required to introduce the product by May 2025.

The author has published significantly in the field of engineering design and capstone projects [4 – 11]. Some recent publications include:

- Reference [4] presents the design of a low-cost 3D printer using off-the-shelf components. The printer is constructed and then used as a demo for a high school STEM outreach project.
- Reference [5] illustrates how design projects can be used to foster self-directed learning (SDL). This paper details how various course design projects are used to help students gain knowledge of high-level engineering software programs through SDL while satisfying ABET outcome 7 to "acquire new knowledge."
- References [6 – 9] detail various senior capstone projects whereby groups of students are partnered with industry and faculty to solve large, complex engineering problems.
- Reference [10-11] describes the design of a multi-stage, parallel shaft, gearbox used as a speed-reducer. The main objective of the project is for the student to experience the open-ended, iterative nature of the design process. This paper further discusses a student-led honors project involving not only the design but also the construction of a low-cost gearbox demonstration unit. The gearbox demonstration unit is designed and built to give future students in the machine design course a visual, hands-on way to understand and internalize the working of gear trains as either speed reducers or torque reducers.

2. Motivation, Need and Requirements for Column Protectors:

Pallet racks (Figure 1.A.) used in warehouses and retail (big-box) stores are subject to damage from the everyday uses that commonly occur in busy warehouse environments. Damaged columns (Figure 1.B.) pose a risk to the public due to the potential for collapse of the rack. The damaged rack must also be replaced, which requires a portion of the retail space to be closed-off for an extended period while maintenance performs the necessary repair. A column guard (Figure 1. C) will be designed to protect the columns at the base where they are most susceptible to damage from frontal and side impacts from forklifts and other impacts.

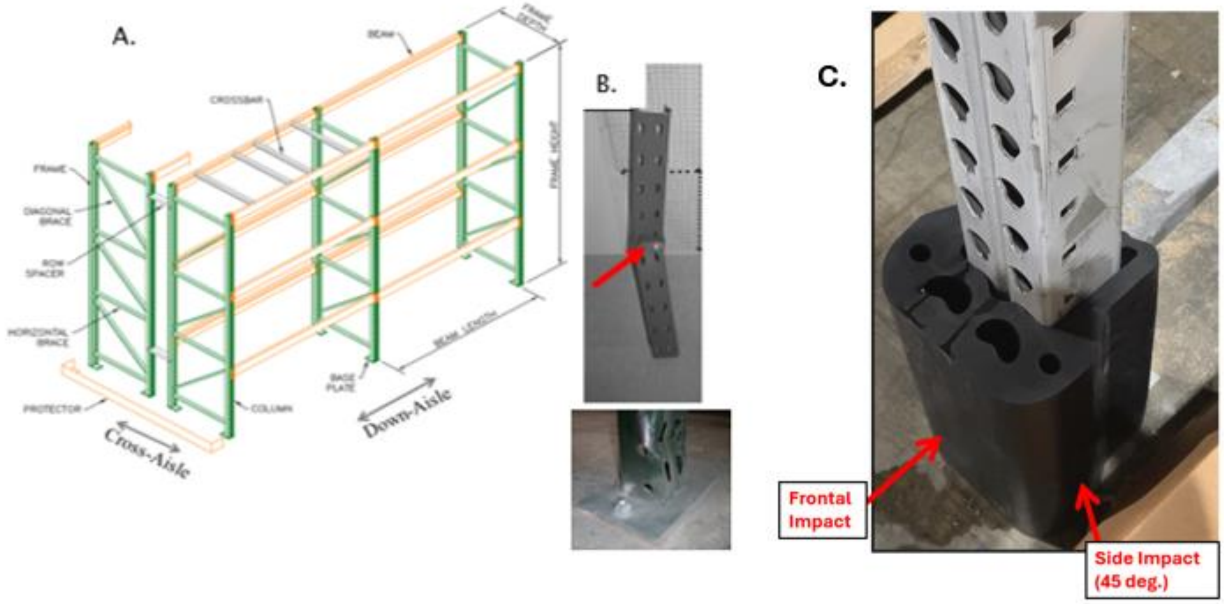


Figure 1: *A*. Typical Pallet-type Steel Storage Rack Configuration (*RidgURak [12]*), *B*. Damaged column from forklift impact, *C*. Final extruded production design installed on rack for field evaluation offers frontal and side impact protection.

There is a wide range of products designed to help protect pallet rack columns from damage. These products include steel reinforced columns, slat-back or offset frames, floor-mounted steel guards and barriers and thermoplastic and elastomeric aftermarket attachable guards. Specific goals of the proposed column guard provided to the students by the industry-sponsor include:

- Must be removable and replaceable with toolless installation (i.e. no anchors or bolts like steel aftermarket guards).
- Minimum length (protection) of 12 inches and must accommodate 70 – 80% of all rack geometries on the market.
- Must outperform existing guards on the market while meeting a *target* price
- Must be durable and withstand multiple frontal and side impacts as shown in Figure 1.c. while protecting against costly column and frame damage.
- The guard must be designed to meet European FEM 10.2.02 Guidelines - a failure (column replacement) criteria of > 5/16 inch (8mm) permanent rack deformation permanent deformation measured over a 40 inch column length [13].
- Must be an extruded elastomer design for cost-effectiveness and performance. The material selected was EPDM elastomer. EPDM has excellent environmental properties (resistance to sunlight, heat and ozone). Additionally, elastomer can store and release more potential energy per unit volume (or unit mass) than other materials such as thermoplastics and metals. This is shown in Figure 2 and discussed in detail in refence [2].

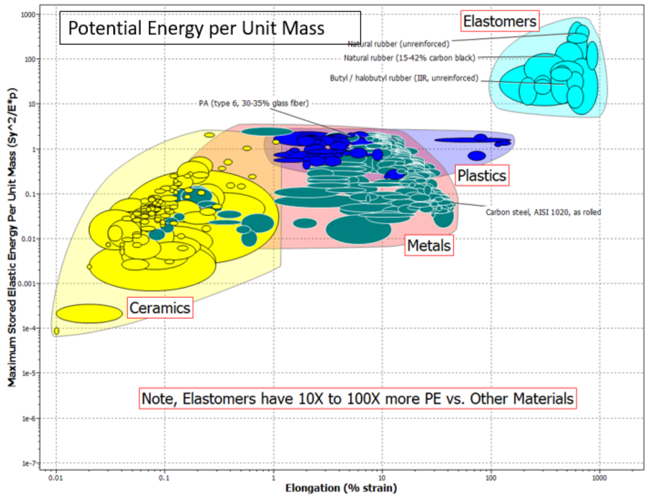


Figure 2: Elastomer was selected for the final column guard material due to its ability to store and release more potential energy per unit volume (or mass) than other materials such as thermoplastics.

3. The Business Team (Final Phase):

The business team consisted of three business students – all with minors in Entrepreneurship [14]. The Entrepreneurship minor consists of three entrepreneurship courses alongside a full slate of other general business classes. The three entrepreneurship courses are first Organizational Innovation, second Entrepreneurial Finance, and third New Venture Creation (the program capstone course). Organizational Innovation dives into what makes an entrepreneur, how to better present and how to find a good idea to pursue. In Entrepreneurial Finance students learn what goes into financing a business and measuring how profitable the business is. New Venture Creation sees the entrepreneurship students take on the task of writing a full business plan around a product or service. While writing the business plan the students conduct interviews with members of their target sponsor to better understand business-related issues they may be having – the business model is then custom tailored to address these needs. Within the Entrepreneurship program, students experience these principles firsthand in their capstone course. This course combines students from two distinct disciplines—entrepreneurship and engineering—to collaborate on real-world projects. Senior students in both fields pitch ideas, with the entrepreneurship students focusing on business potential and the engineering students emphasizing technical feasibility. After the pitches, the teams are formed based on mutual interest, this ensures that entrepreneurship students work closely with engineering peers to deepen their understanding of the technical aspects of product development.

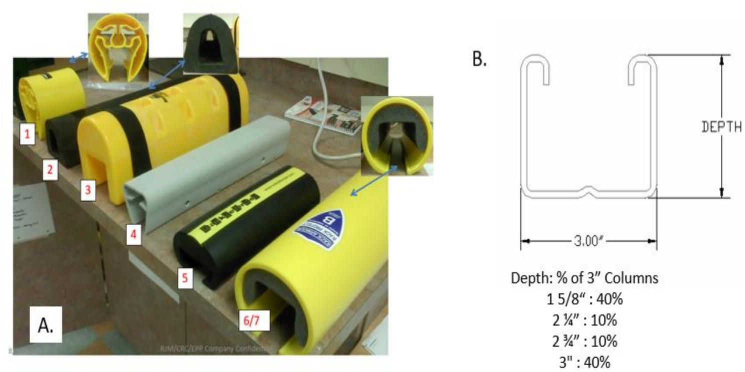
The entrepreneurship students' primary role is to craft a comprehensive business plan for a potential startup based on the selected product or service. To support this, they engage directly with their target customer segment, conducting interviews to gather valuable feedback on the problem space. This feedback is relayed to the engineering teams, allowing them to refine the product or service to better meet customer needs. Collaboration is facilitated through tools like Miro, which enables both groups to brainstorm and develop a shared vision of their target customer.

The group of entrepreneurship students working on the column guard met directly with the industry sponsor and faculty advisor to discuss and learn more about the column guard and to better understand its purpose and target market. Using this information, the team put together a survey and went out into the reginal area and had interviews with different warehousing and industry potential customers. These interviews were crucial to understanding the issues associated with metal storage racks and means of protecting them. The students gathered information on common column sizes, methods of attachment, safety and visibility considerations and many other factors. All this information was passed on to the engineering team in weekly meetings which led to constant design refinement.

In summary, the business team was tasked with (and completed) the following:

1. A detailed business plan which included market analysis, operational and financial plan. The plan also included preliminary ideas for website design and eCommerce as well.
2. Put together a customer survey to understand customer needs. This included call (or site visits) to potential customers. Customer visits included large warehouses and industrial plants. Note, the need for a high-visibility safety-yellow polyethylene overlay came out of these meetings as well as preferences for column attachment). This important customer feedback was provided to the engineering team during weekly team meetings resulting in constant design refinement.
3. Perform a detailed marketing and patent search to determine the current 'state of the art' in terms of storage rack protection. Procure all industry-leading competitor guards for benchmark testing and evaluation (see Figure 3.A.).
4. Storage rack market survey to determine the various column configurations and geometries. Based on this study, students determined that 80% of all racks in conventional warehouse and 'big-box' stores have a width of 3 inch and depths of either 1 5/8, 2 ¼, 2 ¾, and 3 inches (Figure 3.B.).

Figure 3: Results of marketing study. *A.* Current leading column guards, *B.* Standard roll-formed rack cross-section accounts for approximately 80% of all storage rack geometries for retail and warehouse.



5. Set up customer sites for field evaluation. Note, two sites were selected – a large furniture distribution warehouse and an industrial plant. Two unique settings. Figure 4.A. shows installation at the furniture distributor – nearly 500,000 sq. feet of storage space with 30 active forklifts in operation at a given time.
6. Come up with a product name and logo. The business team settled on "Knight Shield" with logo shown in Figure 4.B.

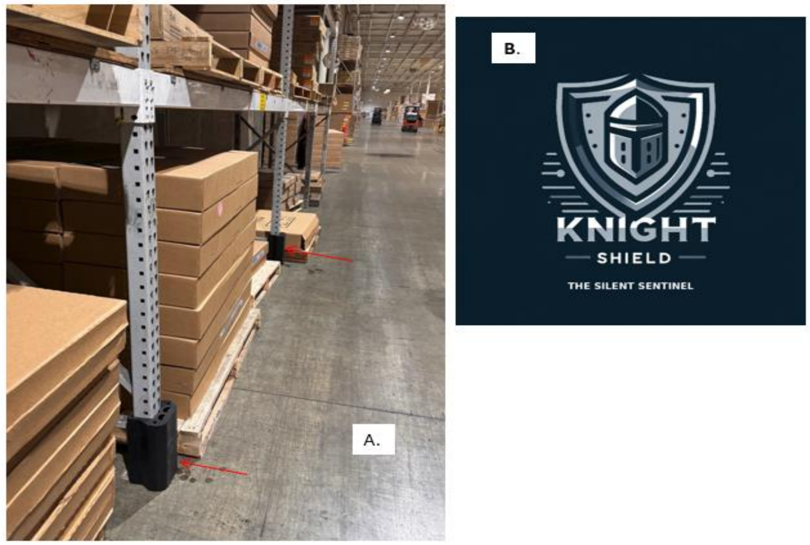


Figure 4: Business Team completed tasks. *A*. Product field studies include installation at a large furniture distribution warehouse, *B*. Product name and logo.

4. The Final Design:

The final column guard design is shown in Figure 1.C. and Figure 4.A. (the field trial installation). Further details are provided in Figures 5 – 7. Figure 5 shows the final guard geometry – a planar symmetric EPDM extrusion. The cores are necessary to meet stiffness and displacement criteria for maximum shock absorption. The final design meets all the design requirements specified in Section 2. Results of final impact testing are detailed in Section 5.

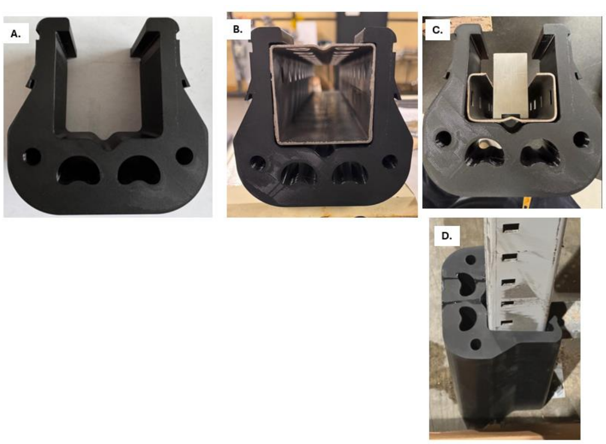


Figure 5: Final geometry of extruded EPDM column guard. *B*. Guard shown installed on largest 3 inch. deep column, *C*. Guard shown on smallest 1 5/8" column, D. Guard shown installed on the most common 2 ¾ inch deep column.

Figure 6 shows optional high-density polyethylene (HDPE) safety-yellow outer sleeve. The marketing team determined this may be a necessary accessory for some customers requiring high-visibility column protection. An added benefit is if the guard is impacted, the HDPE sleeve will show evidence of that impact so the column can be properly inspected (addresses an inspection criteria). The final guard geometry easily accommodates the HDPE sleeve as shown in Figure 6.

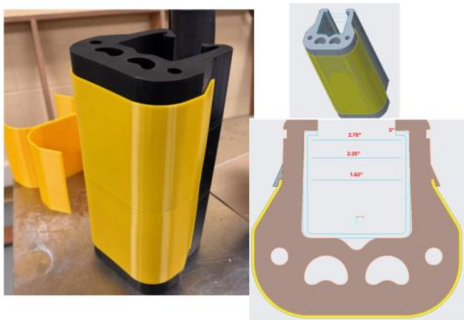


Figure 6: Guard shown with optional safety yellow HDPE outer sleeve for high-visibility and column impact detection.

Finally, the team came up with methods of secondary attachment as shown in Figure 7. This would not be required for column depts of 3 inch and 2 ¾ inch (Figure 5B and 5D). The guard can be properly secured to columns with depths less than 2 ¾ inch by one of these methods.

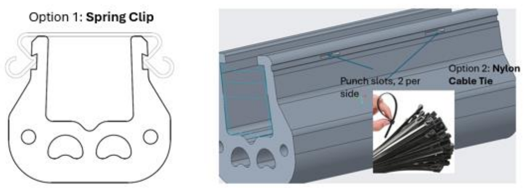


Figure 7: Secondary attachment methods. These methods can be used to better secure guard to columns with depths less than 2 ¾”.

5. The Engineering Team (Final Phase):

A group of four mechanical engineering students were assigned to work on the final phase as part of their senior capstone course. The students worked directly with the business team. Based on feedback from customers and customer surveys provided by the business team, the engineering team finalized the design shown in Figures 5 – 7 above. After the design was manufactured as an extruded EPDM production-intent final design, the team completed a series of tests. Details of these tests have been presented in references 1 – 3 and include the tests shown in Figure 8:

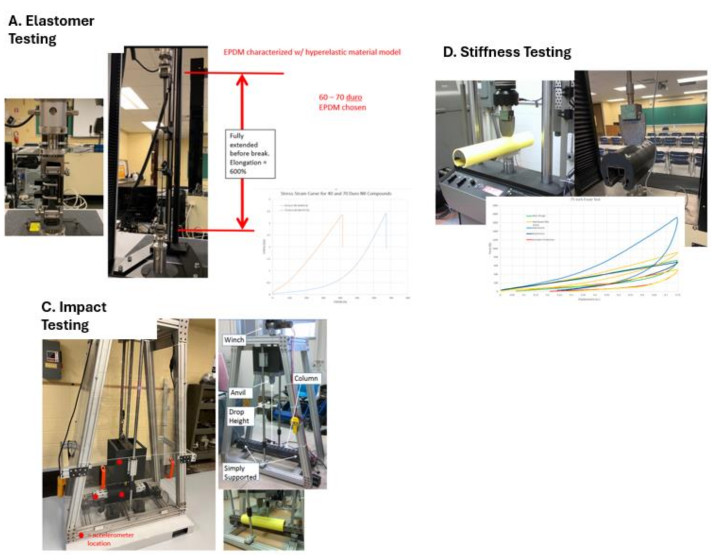


Figure 8: Tests the engineering team performed to validate final design, *A.* elastomer tensile testing on Instron test machine, *B.* Stiffness testing on an MTS 810 test frame, *C.* Impact testing. Note, impact tester designed to FEM 10.2.02 [13] to simulate forklift impact. Students designed and built the impact tester for benchmark testing to determine front and side impact protection of various column guards.

Based on this testing, durometer (stiffness), damping, elastomer type, thickness and final geometry were finalized. The final guard design was then impact tested to measure performance. Details on the design and build of the custom impact tester for testing columns found in refence [3]. The impact tester was built to FEM 10.2.02 standards [13] with a failure (column replacement) criteria of > 5/16 inch (8mm) permanent rack deformation. The potential energy of the impact tester is adjustable via height and suspended weight with a maximum equivalency of a 5,000 lb. forklift impacting a column at 3 mph (the condition used to characterize guard performance).

Impact testing was performed for frontal and 45-degree impacts (Figure 9).

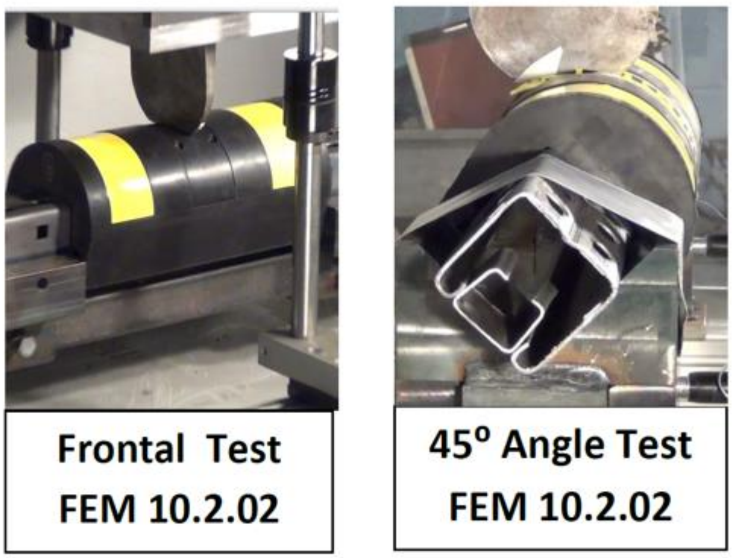


Figure 9: Impact testing was performed for frontal and 45-degree impacts. Impact testing showed reduction in peak acceleration from 700 g to 30 g with guard. Column showed no visible damage after 20 impacts.

Figure 10 shows frontal impacts for the new column guard benchmarked against top competitor guards. Figure 11 shows frontal impact results for the new column guard against the top competitor elastomeric guard. Results showed reductions in peak acceleration of peak impact acceleration from 400 g (no guard) to 16 g with new column guard. The new guard outperformed all the other guards as shown in the figures including the top elastomeric guard on the market. The new guard showed excellent performance for all six impacts while the other guards showed performance degradation with each successive impact due to damage of the guard which hindered its ability to protect the column. Columns tested without the column protector showed damage after a single impact and exceeded the rack replacement criteria (i.e. deformation > 5/16") after 4 impacts.

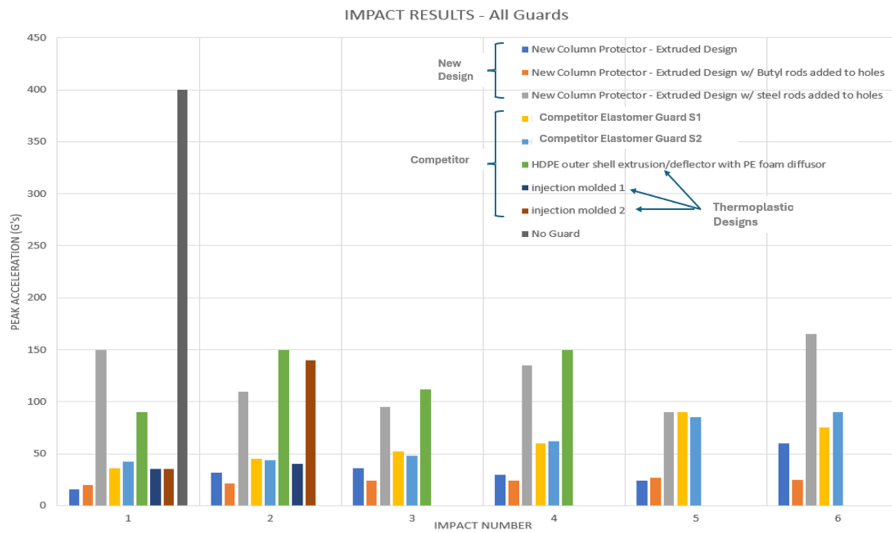


Figure 10: Frontal impact results for new guard and top competitor guards.

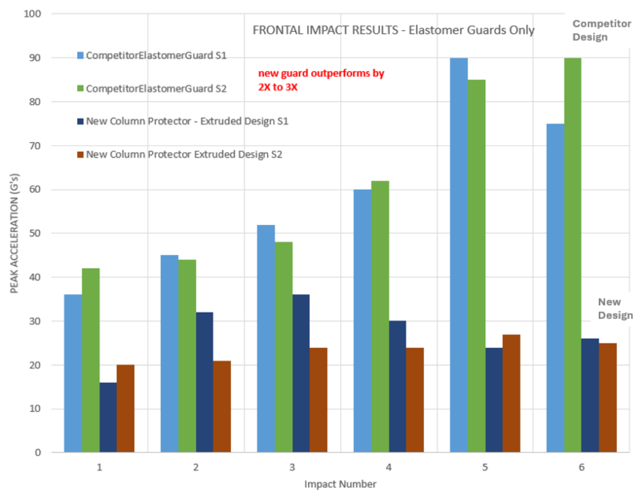


Figure 11: Frontal impact results for new guard and top competitor elastomer guard.

The new guard offers significant improvement for 45-degree impacts – an important advantage since most impacts in a factory or warehouse generally occur at an arbitrary angle (versus just frontal). Figure 12 shows 45-degree impact results for the new guard versus the top competitor plastic guard and top competitor elastomer guard. The new guard shows 2X to 3X improvement over competitor guards. The new guard protected the column for 3 successive impacts while the best competitor guard showed significant column damage (in excess of 5/16 inch) after the same number of impacts.

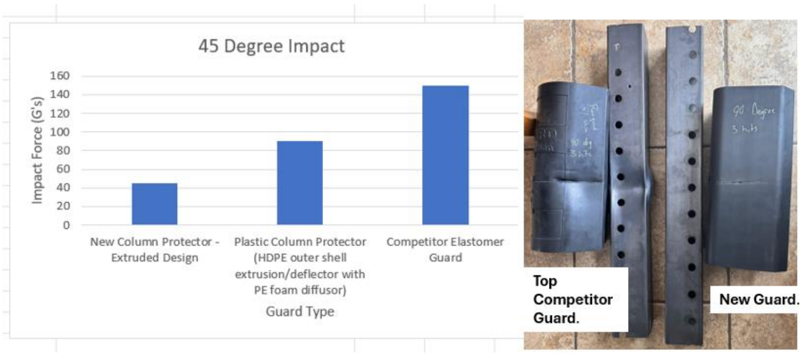


Figure 12: 45-degree impact results for new guard versus top competitor plastic guard and top competitor elastomer guard.

6. Conclusions:

This paper presents results for the final phase of an industry-sponsored senior design project involving the design of a column guard to protect storage racks from forklift impacts. In the final phase, a group of four mechanical engineering students collaborated with a group of three business students. The engineering students were responsible for the final design and test validation while the business students focused on the marketing and business plan as well as customer interaction. The groups of engineering students interacted directly with the business students, holding weekly meetings. Customer visits and surveys arranged by the business team provided crucial information that the engineering team utilized to finalize the design. The final column guard is currently being field-tested at various warehouse and manufacturing plant locations throughout the region. Finally, the group of engineering and business students created a product launch strategy and planned roadmap outlining the steps and tactics required to introduce the product into the market by May 2025.

This project is a transformative experience for students from both disciplines. Entrepreneurship (business) students gain a profound appreciation for the technical skills and problem-solving abilities of their engineering counterparts, while engineering students develop a deeper understanding of what it takes to turn innovative products and services into viable businesses. As Scheer [15] aptly states, “If research results are to be translated into products, entrepreneurship will need to be involved. By entrepreneurship, we understand the ability to implement visions from nothing, so to speak. This calls for entrepreneurship to be combined with attributes such as a willingness to assume risks as well as innovative capability." (Scheer, 2009)

This partnership between entrepreneurship and engineering students underscores the importance of interdisciplinary collaboration in driving innovation. By combining their unique perspectives and skills, these future professionals can develop solutions that not only address pressing challenges but also contribute to improving the world around us. The insights gained through such collaborations lay the foundation for a future where businesses and technologies work together to create meaningful impact.

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