Development and Testing Approach of the Novel Mack Clamp Contact Patch Mechanism

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INTRODUCTION AND BACKGORUND

In the realm of fitness and competitive barbell sports, one of the most critical pieces of equipment is the weight plate retention collar (WPRC), also known as a collar, clamp, or clip. These collars play a crucial role in ensuring that weight plates, loaded onto a barbell, stay securely in place to prevent any accidents or injuries, as demonstrated in Figure 1.

Figure 1. Failed weight plate retention collar from repetitive use

The designs of most WPRCs have evolved from their industrial predecessors, which saw significant improvements only as recently as the 1900s [1,2]. Generally, WPRCs, along with their industrial counterparts, serve the simple function of maintaining their position on a barbell shaft by utilizing frictional forces to prevent any movement [3]. In a gym environment, various exercises such as snatches, cleans, and deadlifts often involve dropping the loaded barbell onto the floor, generating a substantial amount of kinetic energy. Due to the natural gap between the barbell sleeve and the weight plates, a significant portion of this kinetic energy is transferred laterally to the WPRC, resulting in slippage, as depicted in Figure 1, and even complete failure.

To understand this issue better, it's important to note that WPRCs are often considered insignificant accessories by companies that supply gym and fitness equipment. This is largely because the revenue generated from WPRC sales is considerably smaller compared to other fitness equipment and devices on the market. Additionally, for many large companies, the cost of developing a high-quality WPRC outweighs the business benefits. Consequently, the competition in designing and producing reliable WPRCs is stifled by the oligopoly that controls the market and dominates most of the innovation in this space. Adding to this issue, gym owners often see WPRCs as an additional expense that doesn't significantly contribute to their revenue, further reducing the demand for firms to produce satisfactory WPRCs. As a result, participants, end-users, and even professional athletes are left with limited choices when it comes to WPRCs, most of which offer minimal performance, pose safety risks, and hinder athletic progress.

The most critical design aspect of a WPRC is undoubtedly the interaction between the WPRC and the barbell sleeve. This interaction fundamentally determines the quality and user experience of a WPRC by providing resistance against weight plate sliding. In this paper, we present a novel WPRC design, the Mack Clamps, which addresses the most significant criteria for WPRCs "resistance to sliding" by utilizing optimized Contact Patches (CPs), as shown in Figure 2.

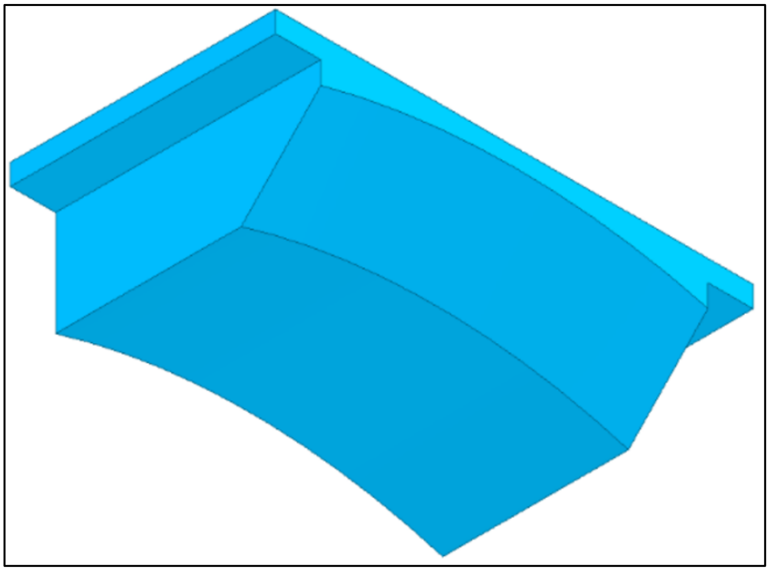


Figure 2. Contact patch CAD model

While the Mack Clamps, as depicted in Figure 3, incorporate several newly integrated technologies and innovations, the primary focus of this work will be on the design process and validation of the CPs, which have resulted in the strongest performance of any known WPRC.

Figure 3. Embodiment of the Mack Clamps

Methodology

The interaction between the barbell sleeve and any given WPRC essentially determines the performance quality. This is not only crucial for recreational applications but can also hold significance for industrial applications [4]. To validate this novel WPRC and assess the tribological performance of the CPs, this work opted for a classical approach, as depicted in Figure 4.

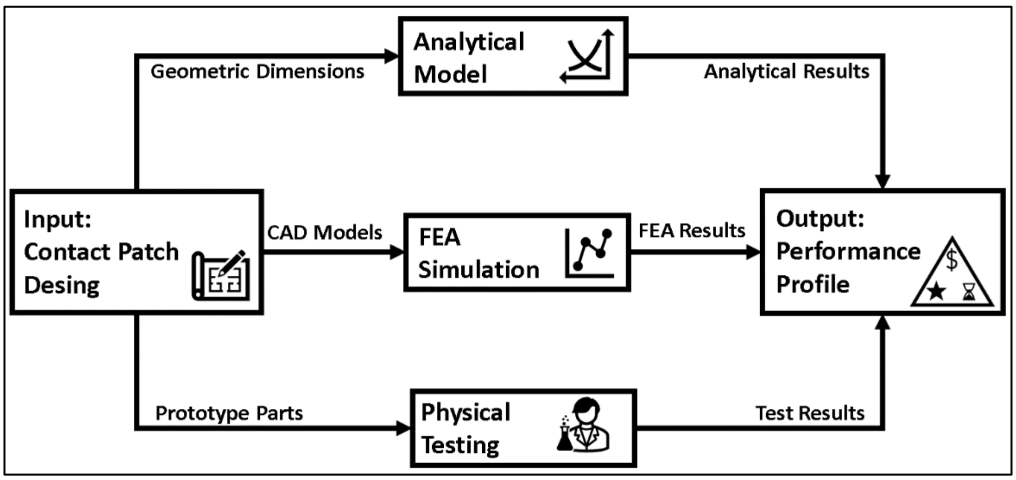


Figure 4. Contact Patch validation approach

This approach encompassed three distinct steps. First, the critical geometry of the CPs was analytically evaluated. Second, the CP function was simulated using Finite Element Analysis (FEA). Third, prototype testing was conducted. The results from these three independent methodologies were compiled and compared to validate the overall performance profile of the Mack Clamps, with specific emphasis on the CPs.

<u>Contact Patch Mechanism Design</u>

The primary objective of the CP mechanism was to provide users with a mechanical advantage while maintaining simplicity with the fewest possible components. This mechanical advantage is critical in the application of WPRCs, as they all adhere to a common rule: the greater the clamping force, the better the collar's performance. Therefore, the decision was made to employ the power screw mechanism to convert the user's input torque into the necessary holding force for the CP mechanism, as represented by Eq. 1:

$$T = \frac{F d_m}{2}\left(\frac{L + \pi \mu d_m}{\pi d_m - \mu L}\right) + \frac{F \mu_c d_c}{2} \qquad (1)$$

Figure 5 below depicts a cross-section of the Mack Clamp CAD assembly, illustrating the general power screw mechanism. The user's input torque, denoted by the red curved arrow, generates a clamping force against the CP, shown by the red straight arrow. Additionally, equal and opposite reaction forces generated by the barbell sleeve are represented by green arrows.

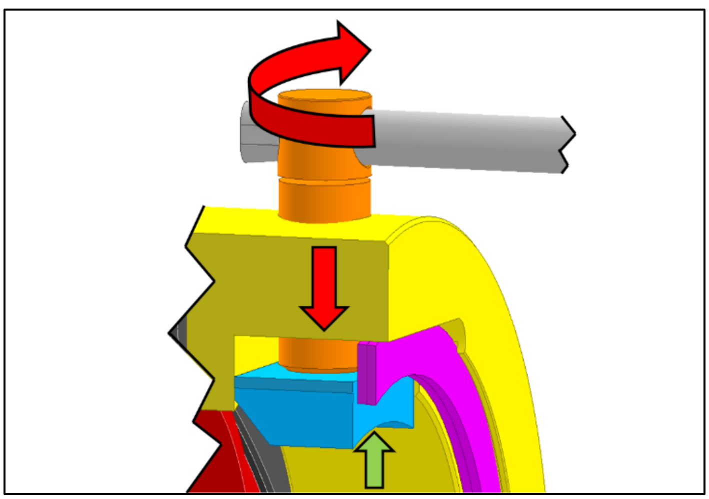


Figure 5 Contact Patch mechanism using the power screw concept

The selection of thread pitch and mating material for the thread was made to create a self-locking thread, ensuring it remains secure during repetitions involving high impact and vibrations while still allowing for a long lifecycle [5]. Furthermore, efforts were made to minimize the frictional forces between the CP (blue components in Figure 5) and the screw (orange component in Figure 5) to enhance performance [6,7]. To further optimize the efficiency of the CP mechanism, the decision was made to triangulate the positions of the opposing contact patches. This triangulation allows the clamping load to disperse both vertically into the barbell sleeve and horizontally, creating an equal and opposite reaction from all three contact patches in the Mack Clamp design. This effect could be achieved using any axially symmetric arrangement of CPs; with three being the minimum number of contact patches needed to generate this effect.

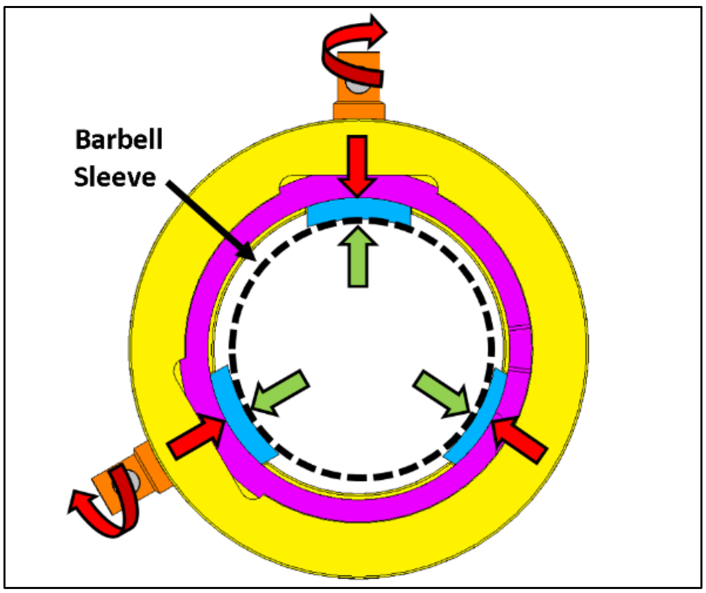


Figure 6. Triangulation of the Contact Pates onto a given barbell sleeve

As shown in Figure 6, two dynamic contact patches apply force against a third stationary contact patch. The outer diameter of the barbell sleeve is represented by a dashed line, and the respective reaction forces are indicated by green arrows. This configuration ensures that the activation of any one of the turnbuckles automatically loads all three CPs equally and simultaneously. Furthermore, this arrangement simplifies the complexity of the validation analysis, as it can be assumed that analysis of one CP will yield valid results for the other two as well.

Analytical Approach

To maximize the grip between a CP and a barbell sleeve while minimizing stress, a concave contact surface was chosen to mate with the cylindrical outer diameter (O.D.) of a standard barbell sleeve [8,9]. This results in a traditional cylindrical mating surface pair, illustrated in Figure 7.

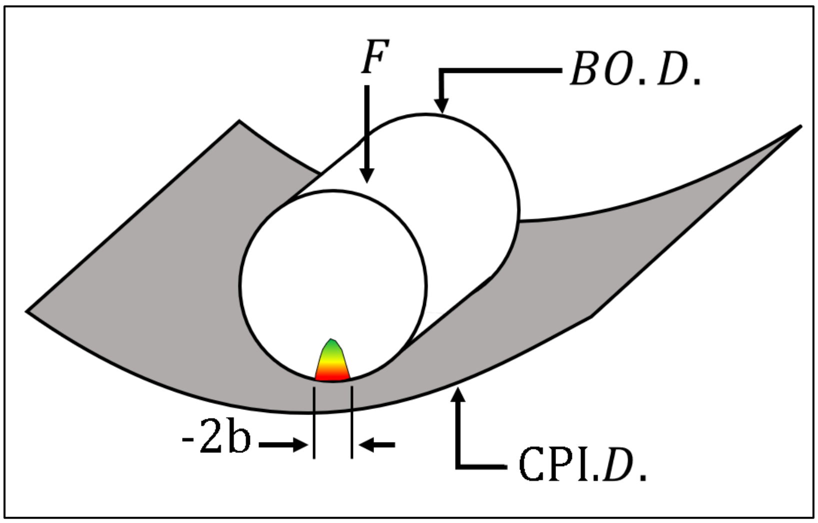


Figure. 7 Hertzian contact of Barbell O.D. and Contact Patch I.D.

This cylindrical contact between two elastic solids, referred to as Hertzian Contact, can be reliably analyzed and modeled using the Hertzian equations provided below. Equation 2 predicts the maximum pressure, while Equation 3 predicts the half-width of the contact area.

$$p_{max} = \frac{2F}{\pi b l} \quad (2)$$

$$b = \sqrt{\frac{2F}{\pi l} \frac{(1 - v_1^2)/E_1 + (1 - v_2^2)/E_2}{1/(BO.D.) + 1/(CPI.D.)}} \quad (3)$$

According to the Hertzian contact theory outlined above, the closer the inner diameter (I.D.) of the CP surface matches the O.D. of the barbell sleeve, the lower the stress concentration in the CP contact surface will be. This alignment could significantly enhance the performance of the CPs. However, when considering the entire contact patch mechanism along with the tolerances of all other components involved, achieving a close match between the CP I.D. and the barbell sleeve O.D. would require much tighter tolerances overall. Tightening the tolerances of all components involved significantly increases production costs. Through manual analytical iterations, it was determined that the ideal CP I.D. for this specific application should be 63.5 mm (2.5 in). Based on having the CPs at minimum design criteria with the loads at maximum operation levels, the Hertzian analytical model predicted a maximum contact stress of 651 Mpa (94.4 ksi) and a contact area width of about 2.54 mm (0.1 in).

<u>FEA Validation</u>

While the analytical modeling yielded favorable results for the direct contact surface, uncertainty still existed regarding the remaining aspects of the CP geometry. To address this, FEA was performed using the open-source software PrePoMax to identify any irregular or unexpected stress concentrations within the CP geometry [10]. To optimize the simulation's processing time, several strategic adjustments were made to the simulation model.

First, the symmetrical properties of the CP mechanism were leveraged to enable the simulation to be divided in half, as illustrated in Figure 8. Appropriate boundary conditions and forces were applied to create the most realistic scenario. Using a single partition enhanced the accuracy of the contact surface while ensuring uniformity in the CP's irregularly shaped features. Given the well-established and reliable analytical model for Hertzian contact in this scenario, an autogenerated mesh with maximum element sizes up to 1.27 mm (0.05 in) was employed to further reduce calculation time and load.

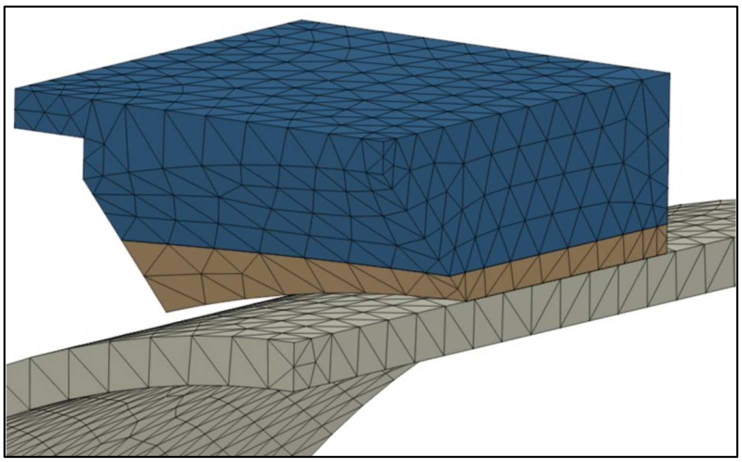


Figure. 8 PrePoMax FEA simulation set up for the Contact Patches

As anticipated, the results of the static FEA analysis closely mirrored those of the analytical model [11], with a maximum Von Mesis stress of 637.8 MPa (92.5 ksi) concentrated along the center of the contact area, as indicated in Figure 9. This slight variation from the analytical model is attributed to the differences in the CP geometry, a factor the analytical model cannot account for. More crucially, no unexpected stress concentrations were detected due to the edges, corners, and tapers incorporated into the CP geometry.

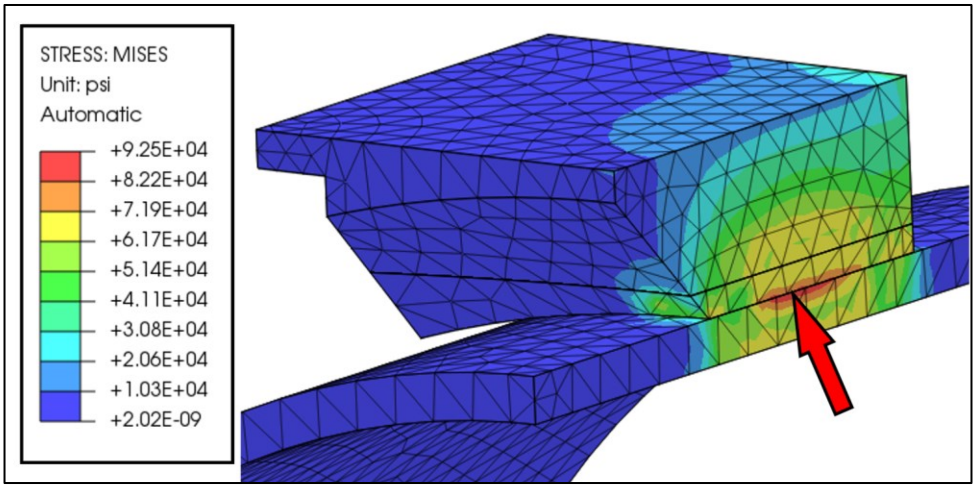


Figure. 9 PrePoMax FEA results showing Von Mesis stress concentration

Moreover, the FEA model, as depicted in Figure 10, suggested a contact deformation width of approximately 2.54 mm (0.1 in). These results not only reaffirmed congruence with the analytical model but also provided the necessary confidence to proceed to the prototyping and testing stage of this project.

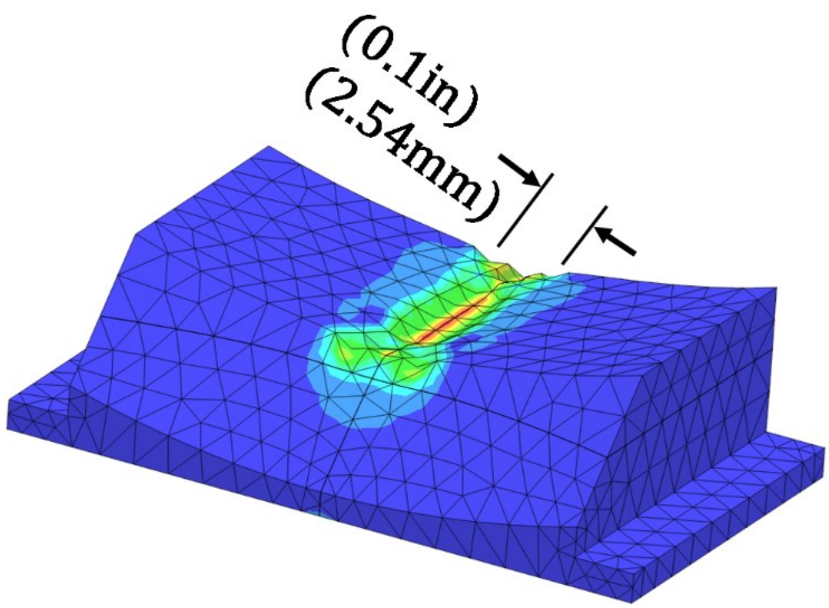


Figure. 10 PrePoMax FEA results showing deformation as a scale factor of 80

Engineering Testing

Purpose and Scope of Testing

Once the theoretical and computational approaches of CP design provided convergent results, the natural progression was to validate the physical CP performance. To achieve the irregular CP geometry and induce natural surface roughness for enhanced holding force [12], casting was chosen as the manufacturing method instead of machining to further reduce costs and manufacturing time. However, concerns arose about the material properties and porosity of cast components. If the cast CPs did not closely meet the material specifications, it would significantly impact their ability to grip a barbell sleeve, potentially necessitating changes in the planned manufacturing approach. Validation testing was deemed necessary to ensure that the casting process for CPs met the specific engineering / material requirements. The testing scope focused on CP hardness and CP function to validate the holding force of this novel WPRC.

Testing Setup

First, test coupons from the production batch underwent hardness testing according to standard procedures, as shown in Figure 11, to verify that the CP material properties met the required specifications [13].

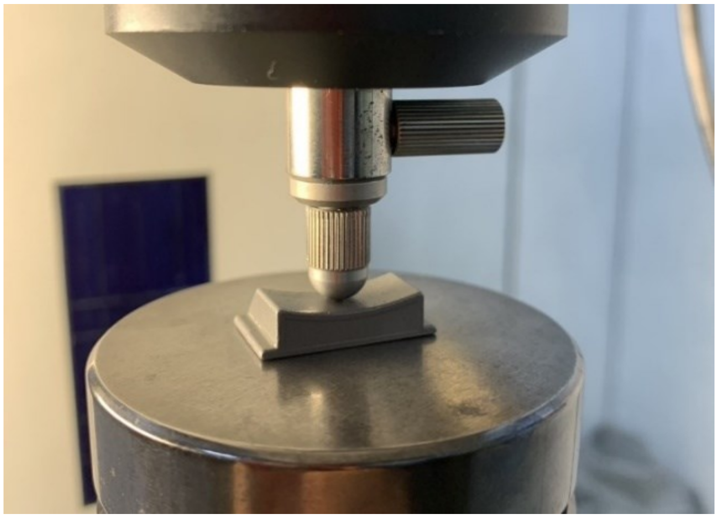


Figure 11. Rockwell-B hardness testing of the CP

Second, a unique testing setup for WPRC was implemented to measure the holding force performance of the Mack Clamps using the novel CP mechanism. Figure 12 illustrates the WPRC testing setup using a universal material testing machine. In the diagram, component 1 is the coupling adopter connecting the modified barbell sleeve to the load cell. Component 2 represents the third-party barbell sleeve, while component 3 is a third-party cast iron Olympic weight plate, and component 4 is a base made of simple alloy steel tubing.

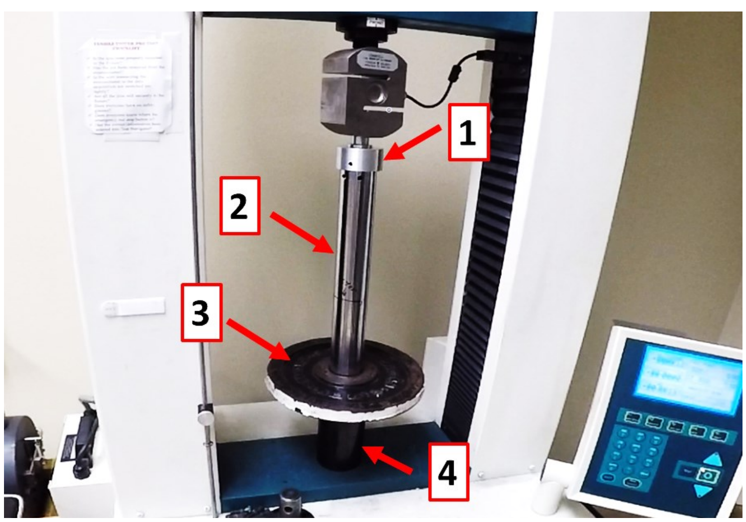


Figure 12. Weight plate retention collar setup

This testing setup deliberately restricts the physical interaction of the Mack Clamps to only third-party components, namely the barbell sleeve and the Olympic weight plate. This decision was made for two key reasons: to maintain objectivity and realism while testing the Mack Clamps and CP mechanism and to allow others to replicate this testing using publicly available components that are critical to the setup. A detailed engineering drawing of this testing setup, with the corresponding numbers, is also provided in Appendix A for further reference.

Testing Procedure

For this testing, a Tinius Olsen H100K-S model was employed, operating at a speed of 150 ± 30 mm/min (0.05 ± 0.1 ft/min) in accordance with ASTM D1894 standard for all test trials. Although ASTM D1894 was initially developed for determining the coefficient of friction between two surfaces, it was assumed that this machine travel speed would be suitable for barbell clamp testing, as the frictional force is what keeps the clamp securely in place against the barbell sleeve. Given that this testing is the first of its kind, no other reference existed for testing WPRC.

Initially, the complete assembly of the Mack Clamps was evaluated based on the categories listed in Table 1.

Category	Value
Claimed Weight	0.454 kg (1.0 lb)
Actual Weight	0.467 kg (1.03 lb)
Full Engagement Length Distance	11.6 mm (0.455 in)
Fit on 1.9” O.D. Bar	Yes
Serviceable	Yes
Shock Absorbing	Yes
Rotational Degree of Freedom	Yes
Contact Surface Material	Alloy Steel

Table 1. Mack Clamp pretesting evaluation

To focus on CP performance, the Dynamic Shock absorption system of the Mack Clamps was disassembled and set aside. This was done to prevent the shock absorption system from interfering with the extracted load vs. distance graphs. Next, two hex screws of the same size and thread pitch (3/8-16 UNC) were used to replace the original screw handles to apply reliable and repeatable torque to the CP mechanism. The 3/8-16 UNC hex screws were lubricated with Rapid Tap to reduce the effects of thread friction. Torque was applied to the CP mechanism using the AC Delco torque wrench to tighten the collar against the barbell sleeve, as shown in Figure 13.

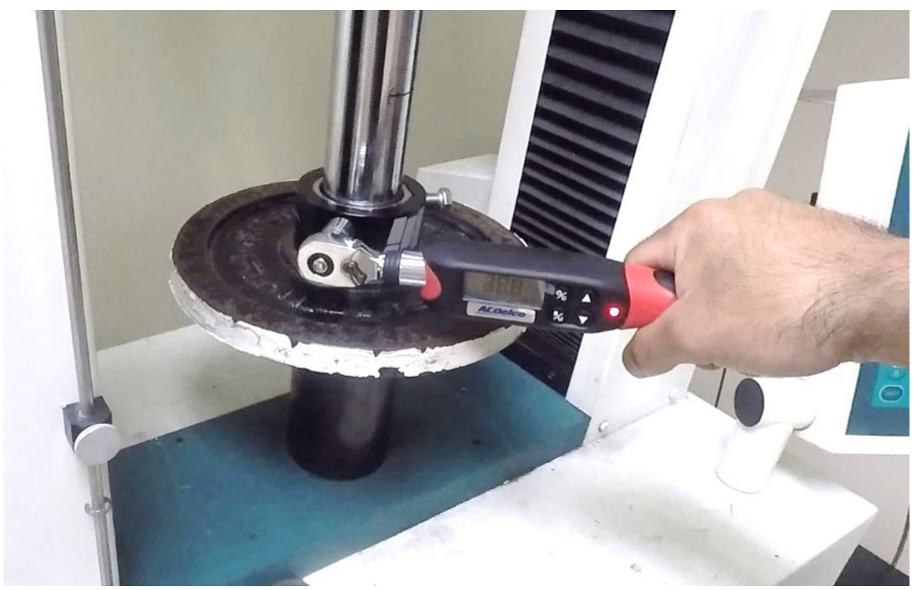


Figure 13. Installation of the Mack Clamps using a torque wrench

Both hex screws were torqued to the required test trial values. This process was repeated for all other torque values: 6.7, 13.5, 20.0, and 27.1 N-m (5, 10, 15, and 20 ft-lb). When the desired input torque was applied, the machine stroke was activated simultaneously with the data acquisition sensors. The machine stroked the clamp against the weight plate until a slip between the barbell sleeve and the WPRC occurred. After detecting slipping, the machine continued its stroke at the given input speed for another 10-33 mm (.39-1.18 in) before being manually stopped. Figure 14 displays the stroke of the barbell sleeve during a single test run by indicating the movement of a line mark on the barbell sleeve.

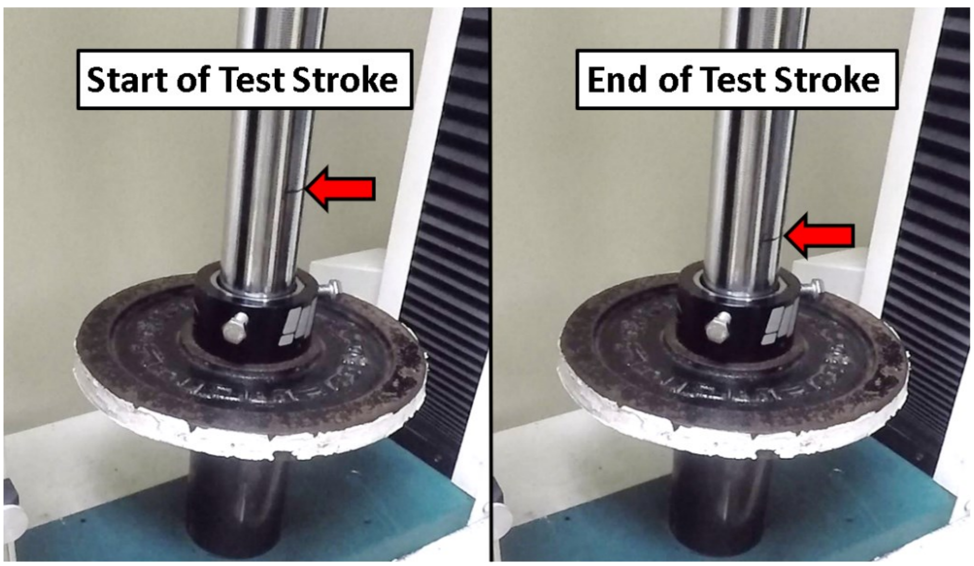


Figure 14. Test stroke of the Mack Clamp testing process

Between trial runs, a visual inspection was conducted on the barbell clamp CPs and the barbell sleeve to ensure no significant damage occurred. The barbell sleeve was brushed down with a plastic brush to remove potential debris. This process was repeated 3-5 times for each specified torque value per testing procedure.

As a final set of tests, the original torque handles of the CP mechanism were reinstalled and hand-tightened with maximal effort. Since the Mack Clamps and the CP mechanism are designed to work purely by hand, it was crucial to determine the holding force against the barbell sleeve using a hand-tight input torque. Hence, 4 sets of hand-tight torque testing were performed to account for variability. While hand-tight torque may not provide scientific reliability, it was essential to obtain a ballpark estimate of what is realistically achievable by hand compared to a torque wrench.

Test Results

Overall, the testing results align with expectations, primarily due to the simplicity of the CP mechanism design and adherence to common engineering principles.

Testing data

Data from the load cell was compiled and graphed to visualize the interaction between the CP mechanism and the barbell sleeve. A clear trend emerged once the testing data was plotted, as shown in Figure 15. The holding force of the CPs against the barbell sleeve exhibited a linear increase with the stroke of the testing machine, followed by a peak and a sudden drop. The peak represents the maximum static holding force provided by the CP, determined by the input torque and the static coefficient of friction. Subsequent fluctuations in sliding holding force remained within a consistent range, closely related to the CP dynamic coefficient of friction [14].

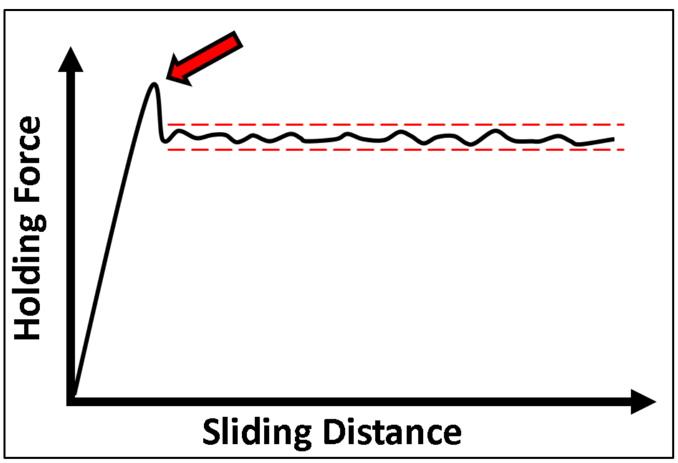
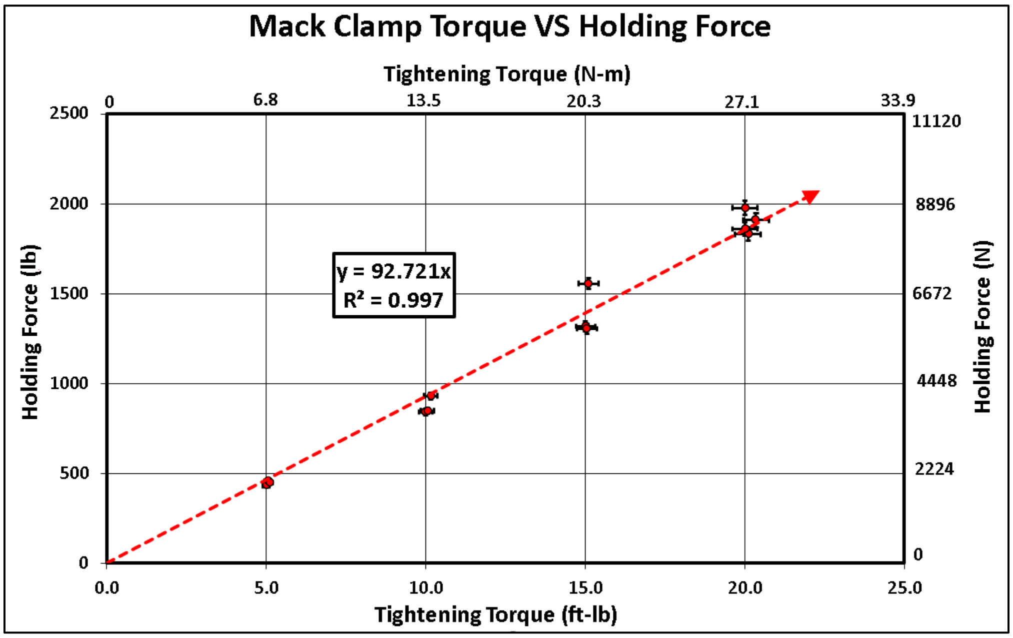


Figure 15. General form of Mack Clamp Contact Patch testing data

For each test run, the peak holding force highlighted in Figure 15 was recorded as the single data point representing the respective trial. The compiled graphs of each test run can be found in Appendix A for further reference.

Interpolated performance graph

To offer a comprehensive representation of CP performance, a graph plotting each peak holding force extracted against the corresponding CP mechanism tightening torque was created. The resulting graph, displayed in Graph 1, serves as the most objective and concise reference to convey the Mack Clamp CP mechanism's performance.



Graph 1. Tightening Torque VS Holding Force of the Mack Clamps

The data points in Graph 1 feature a 1% maximum error for both holding force measured by the Tinius Olsen load cell and the tightening torque applied by the AC Delco torque wrench, as indicated by the respective error bars. The trend line, which originates from the origin (y-intercept at zero), Y=92.721X, interpolates the theoretical expected holding force of the CP mechanism concerning the applied tightening torque of both handles / turnbuckles. It's important to note that due to physical material limits, this interpolation cannot extend indefinitely. High enough tightening torque may cause deformations in the

CP mechanism components and cause a deviation from the trend line. Therefore, it is not recommended to interpolate the holding force beyond 61 N-m (45 ft-lb).

Peak Performance

While torque input using a torque wrench provided an objective and reliable baseline for evaluating the Mack Clamp and CP performance, it may not fully reflect the real-world performance when tightened by hand. The CP mechanism was designed for users to hand-tighten the Mack Clamps with, and using a torque wrench could result in an unrealistic scenario with extremely high input torque, which might not be feasible by hand. Thus, a series of hand-tightened tests were conducted toward the end of the testing to assess the expected peak performance.

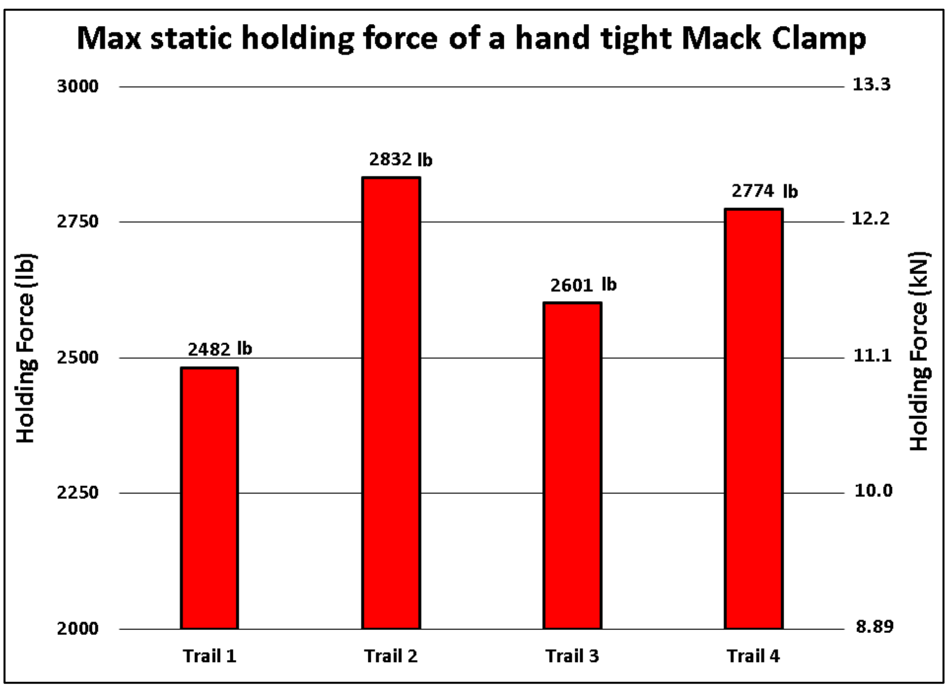


Chart 1. Maximum static holding force of a hand tight Mack Clamp

Based on the testing results displayed in Chart 1, it can be concluded that the CP mechanism is efficient enough for a mid-level athlete to achieve a peak holding force of up to 12.6 kN (2832 lb) from the Mack Clamps when hand-tightened. The average hand-tightened holding force was 11.9 kN (2672 lb), with the lowest result at 11.0 kN (2482 lb). These findings suggest that the Mack Clamps can be labeled as "The World's Strongest Barbell Collar" and "The Strongest Barbell Collar Ever Made." Furthermore, based on these results, it is estimated that the Mack Clamps, utilizing the CP mechanism, offer a peak performance twice as high as any existing barbell collar currently available on the market.

Contact Patch Performance Profile

Based on the design information obtained through analytical modeling, numeric modeling, and engineering testing, a performance profile for the Contact Patches (CPs) was established. Three primary criteria were taken into account to create this performance profile: manufacturing cost, peak strength, and endurance. These three criteria are considered fundamental in summarizing the performance of the CP design and, by extension, any WPRC in general.

An ideal performance profile would thus achieve a balance between Manufacturing Cost, Peak Strength, and Endurance, as depicted in Figure 16.

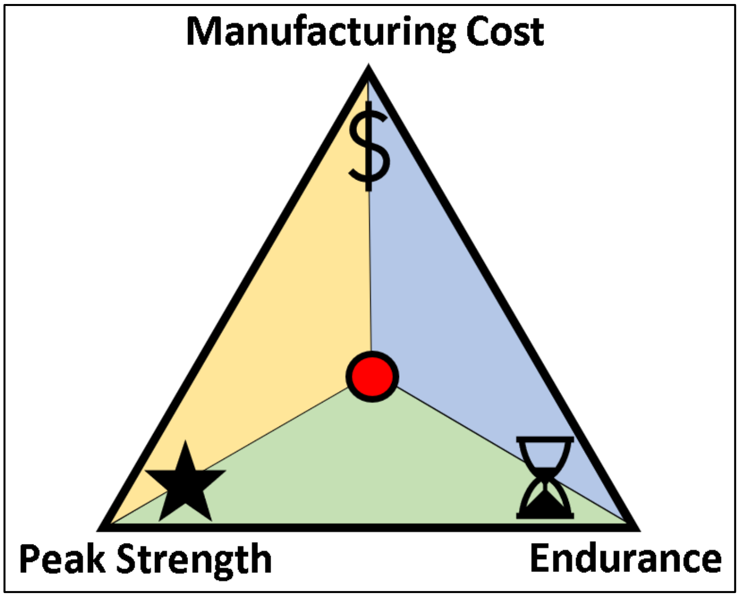


Figure 16. Ideally balanced Performance Profile of a given Contact Patch

Manufacturing Cost

The CP faces significant demands as it must serve multiple functions and withstand extreme loads simultaneously. Typically, such high-performance requirements necessitate strict control of material properties and tight geometric tolerances, leading to a substantial increase in manufacturing costs. These demands usually preclude the possibility of casting the product. However, due to the specific steel alloy selection and secondary heat treatment options, casting was made feasible for manufacturing while still meeting stringent engineering requirements, resulting in cost-effective production of CPs.

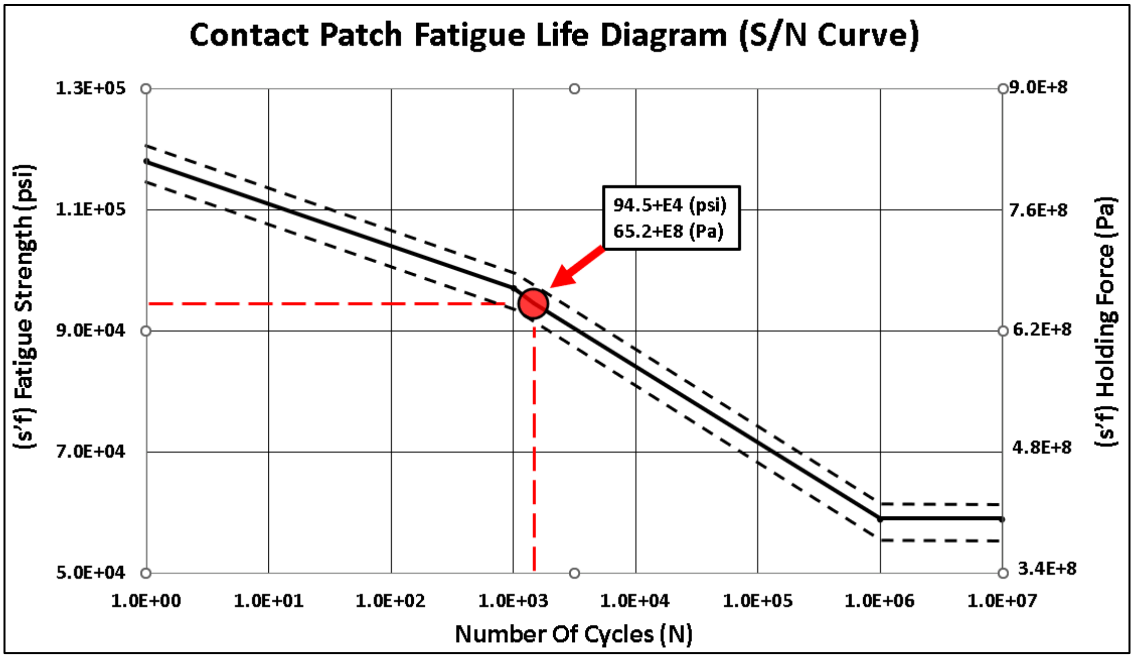
Peak Strength

The paramount objective of developing Mack Clamps was to introduce a WPRC with significant strength that could make a substantial impact in the strength training community. The CPs' peak strength was the primary focus of this product development, and based on the gathered data, it is reasonable to conclude that Mack Clamps possess unrivaled peak strength in the WPRC category. This remarkable peak strength is achieved through CP performance initiated by the CP mechanism as a whole. Although there is room for further enhancing CP strength, it would come at the cost of either increased manufacturing cost or a reduction in performance endurance.

Endurance

While peak strength is a top priority for the CP, endurance is also crucial to the product's end-users because it defines its utility. To optimize peak strength and reduce manufacturing costs, it was decided to sacrifice the endurance performance of the CPs. The question remained as to how much of the CP's endurance strength should be sacrificed and what would constitute a reasonable minimum endurance profile.

Following internal discussions and consultations, it became evident that the CPs' fatigue life should at least fall into the high cycle fatigue region to ensure satisfactory service life. However, since there is a direct trade-off between peak performance and fatigue life, it was decided to optimize the material to be as close as possible to the short cycle fatigue limit. Based on material testing, analytical modeling, and the derived fatigue life diagram as shown in Graph 2, the CPs' fatigue life, at peak performance use, is estimated to be between 1000 to 2000 cycles.



Graph 2. Fatigue life analysis of CP though cyclical load at peak performance parameters

To further validate the estimation of cycle fatigue limit, a crude comparison of the FEA results was made to the physically tested CPs. The highest worn regions of the physical CPs were highlighted and overlaid to the FEA model for comparison. This highlighted region does not include the removal of surface coating, but rather specifies the physical wear observed. Vice versa, the highest stressed regions of the FA model were overlaid to the physical CPs to further evaluate the comparison as shown in Fig. 17. This qualitative comparison further improved the confidence of the CP endurance life.

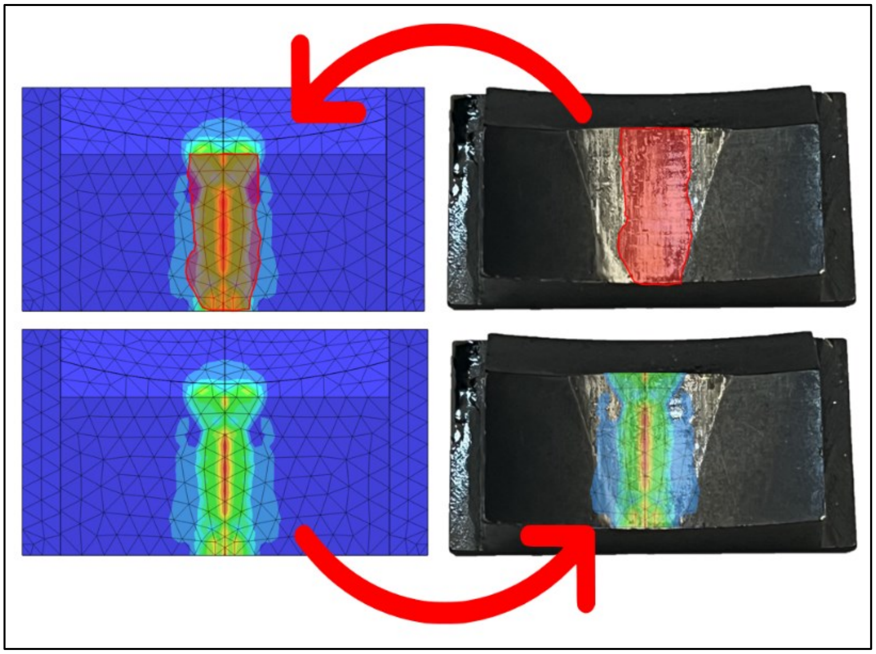


Figure 17. Over lay of physical testing and FEA simulation of the Contact Patches

Based on analytical results and the qualitative comparison, it is estimated that the CPs of the Mack Clamps can provide peak performance for approximately one year of use, and beyond that point, peak performance cannot be guaranteed. Nonetheless, the endurance of the CPs is expected to surpass that of any WPRC using rubber or plastic for contacting and gripping a barbell sleeve.

To compensate for the limited endurance of the CPs, the Mack Clamps feature serviceability within the CP mechanism design. This allows end-users to easily replace any worn-out CPs, ensuring extended peak performance.

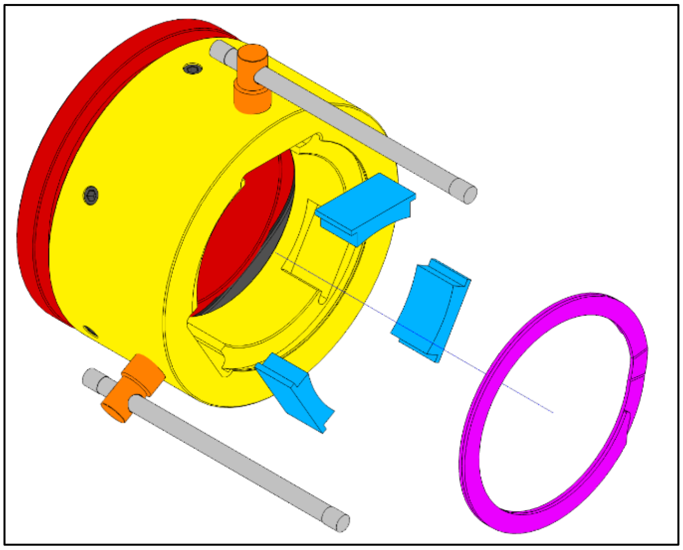


Figure 18. The serviceability and replacement of worn-out Contact Patches

Contact Patch Performance Profile

Taking into account manufacturing cost, peak performance, and endurance, the performance profile of the CPs was evaluated to provide a realistic visual representation, as shown in Figure 19.

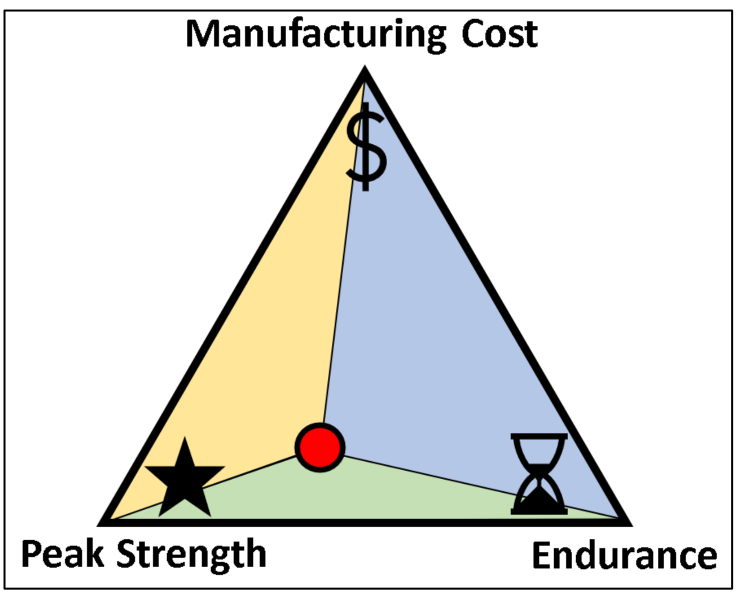


Figure 19. Derived Performance profile of the Mack Clamp Contact Patches

As indicated by the red circle in the figure, manufacturing cost was significantly reduced through the casting method, while still achieving extremely high peak strength. Endurance of the CPs was the main sacrifice to attain exceptionally high peak performance with the given cost-effective production method. Overall, this performance profile was considered ideal for the Mack Clamps and the CP mechanism.

Discussion

Testing Approach

While this paper limited the testing of the CPs and the CP mechanism to the discussed testing setup, further field application testing was also conducted. However, due to limited resources, field and real-life application testing could not be performed with data acquisition and sensors. It is understood that field testing, in the end, is the best indicator of the specific performance demands of the CPs. With that said, no testing standard currently exists for the performance of WPRCs. Therefore, consensus would need to be reached on the most applicable and objective testing methodology. In general, it can be assumed that this testing setup, as described in the paper, has a direct and strong correlation to the field performance of the Mack Clamps and CPs.

Furthermore, it is believed, based on visual evidence, that the strong grip of the CP, in addition to the forced sliding, affected the surface properties of the given barbell sleeve. This means that as the testing continued, the surface of the barbell sleeve became smoother due to wear. This, in turn, could have reduced the maximum holding force capacity of the Mack Clamps towards the end of testing. This is something that could be solved by having multiple barbell sleeves available as replacements. However, in this instance, no replacement was available, and testing continued with the same provided specimen.

MACKEY INNOVATIONS

Endurance

As discussed in the "Contact Patch Performance Profile" section of this paper, the weakest point of the CP design is its endurance. However, it is important to note that the endurance of the CPs is relative to other components traditionally design and manufacture out of steel. In other words, when directly comparing the CP's performance to that of other WPRCs, it can be said with great confidence that the endurance of the CP is well beyond industry standards of WPRCs

Future work

Mack Clamp comparison to other Weight Plate Retention Collars

While the results obtained from the testing discussed in this paper strongly suggest that the Mack Clamps, with the CP mechanism, are the world's strongest WPRC, testing needs to be done to prove this objectively. As of the writing of this paper, testing is being conducted to compare the performance of the Mack Clamps to 12 other industry-leading WPRCs. The goal is to publish these findings as soon as possible to supplement claims and results found in this work specifically.

Dynamic Shock Absorption and Rotational Degree of Freedom

The Mack Clamps contain two more significant novel attributes: the Dynamic Shock Absorption System and the Rotational Degree of Freedom, which are outside the scope of this paper. While figures of these two concepts can be found in Appendix C, future work must be done to quantify and prove the performance and utility of these two integrated features objectively. Based on preliminary field testing, it is believed that these two novel features significantly aid the performance of the Mack Clamps and the CPs in general.

Establishing design and testing standards for Weight Palte Retention Collars

WPRCs play a vital role in athlete-safety and athlete-performance. While other critical strength equipment used are significantly overbuilt to prevent damage or injury, WPRCs are the only equipment that still regularly fail and pose significant risk. Therefore, future work must be done to establish a working standard of WPRC design and WPRC testing to mitigate the risk of injury to strength athletes and their surrounding participants.

<u>Development and Testing of a 2.5kg Competition Grade Version</u>

Governing federations ask that the WPRC used in competition be exactly 2.5kg (5.5lb). Therefore, to allow local, state, national, and international level competitions the ability to use the Mack Clamps, a 2.5kg (5.5lb) standard version of the Mack Clamps must be developed. This is a prioritized future goal of this ongoing project.

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NOMENCLATURE

T	Input Torque by the user
d_c	Mean collar diameter
d_m	Mean thread diameter
L	Lead of the screw
F	Activation Force
μ	Coefficient of friction for the thread
μ_c	Coefficient of friction for the collar
p_{max}	Maximum contact pressure
b	Half width of contact area
l	Length of contact area
v	Poisons ration
E	Modulus of elasticity
$BO.D.$	Barbell Sleeve O.D. 50mm -1%
$CPI.D.$	Contact Path I.D. 2.5”±.005”

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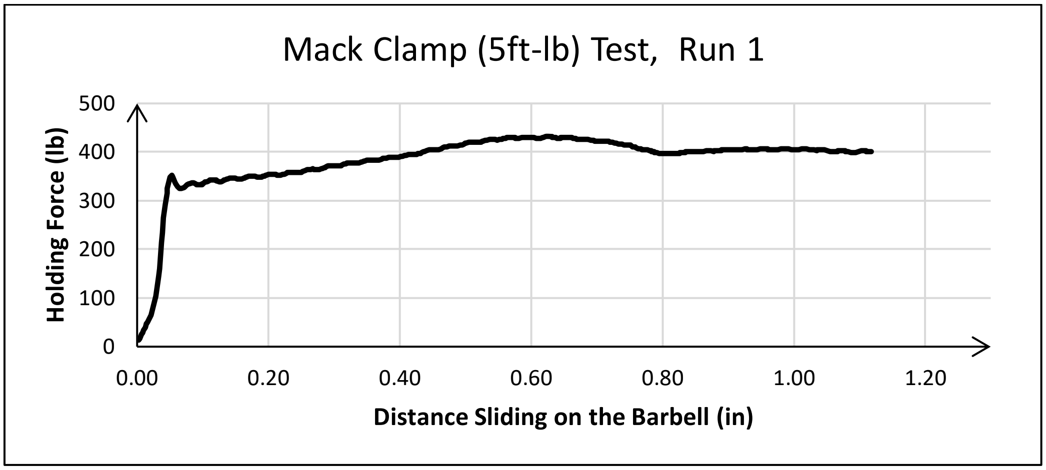
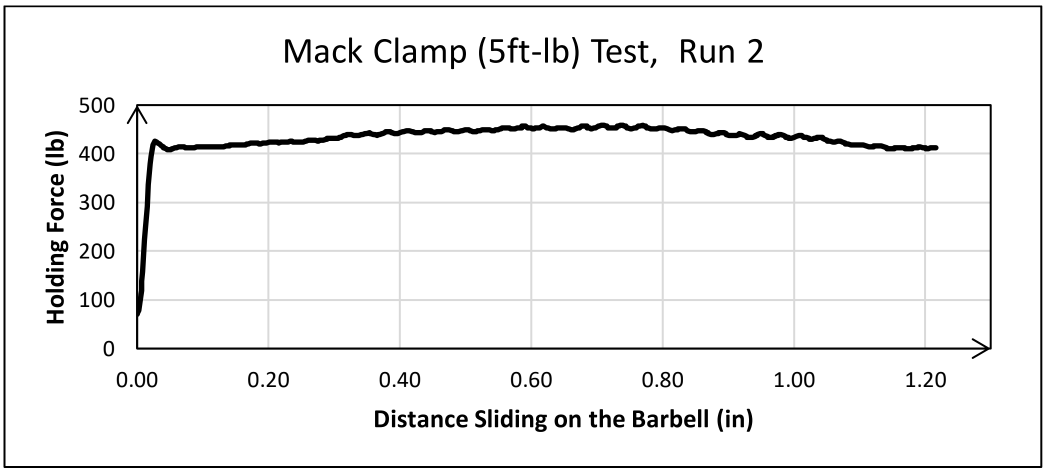
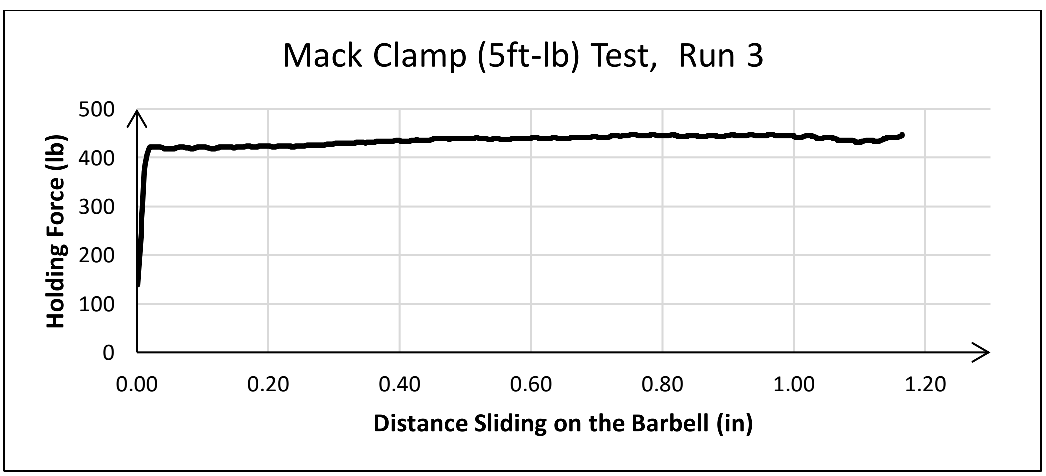
Appendix A: Testing Graphs and Drawings



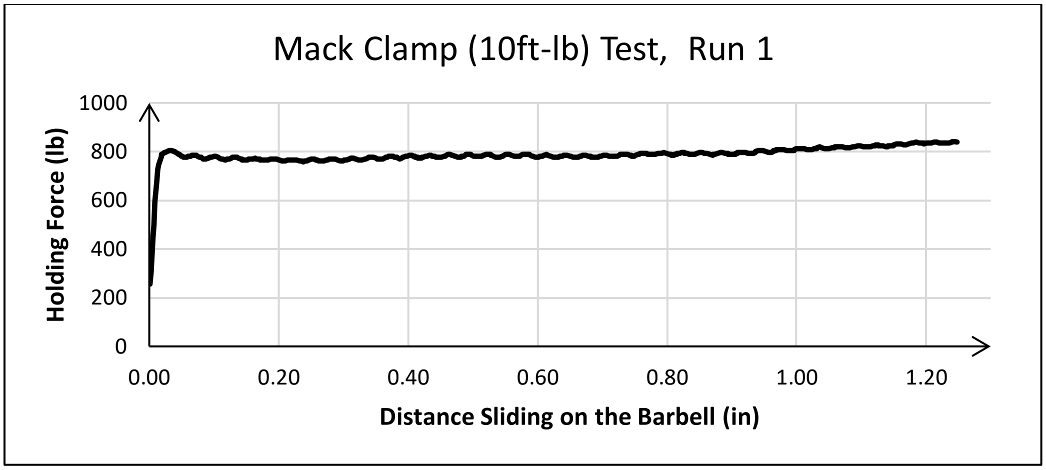
Graph 3- Mack Clamp 5ft-lb, Run 1



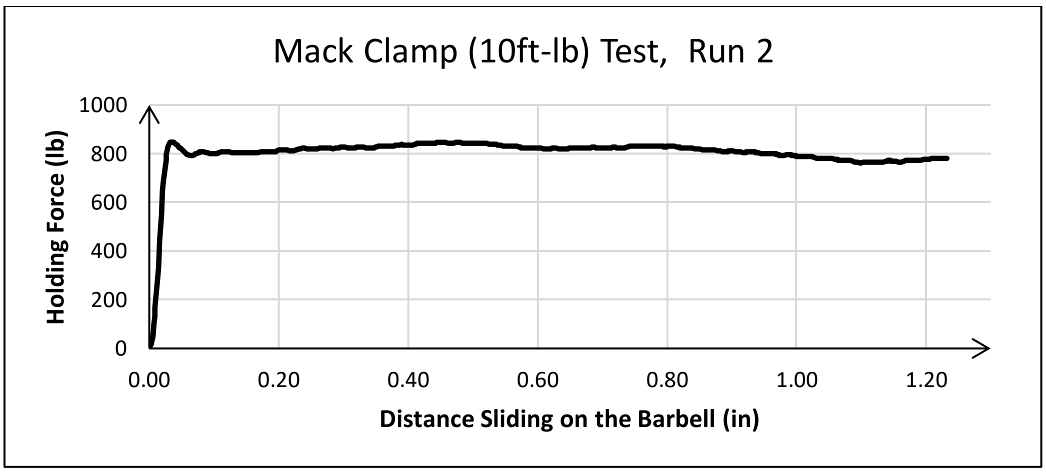
Graph 4 – Mack Clamp 5ft-lb, Run 2



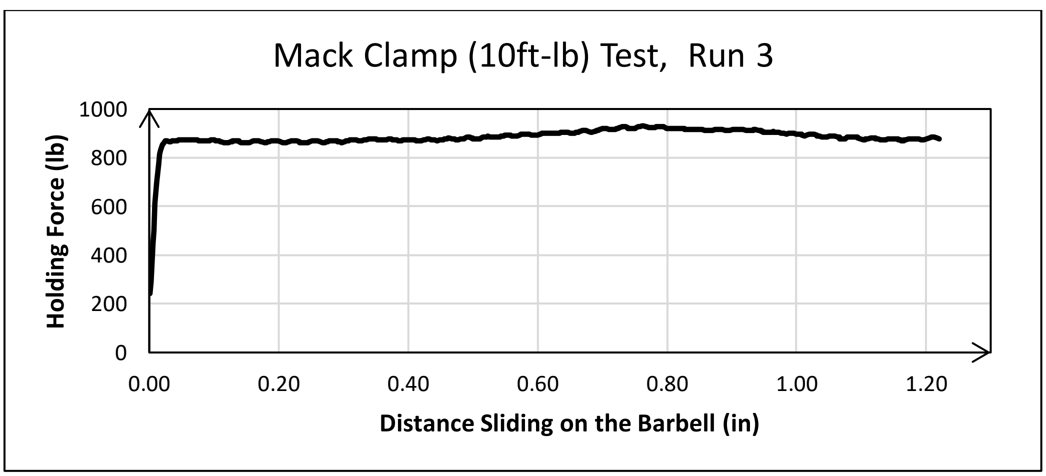
Graph 5 – Mack Clamp 5ft-lb, Run 3



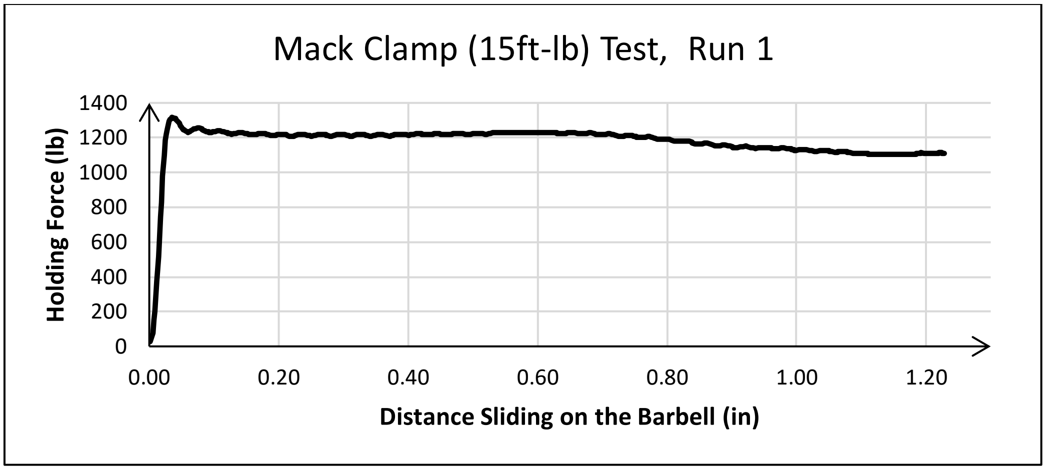
Graph 6 – Mack Clamp 10ft-lb, Run 1



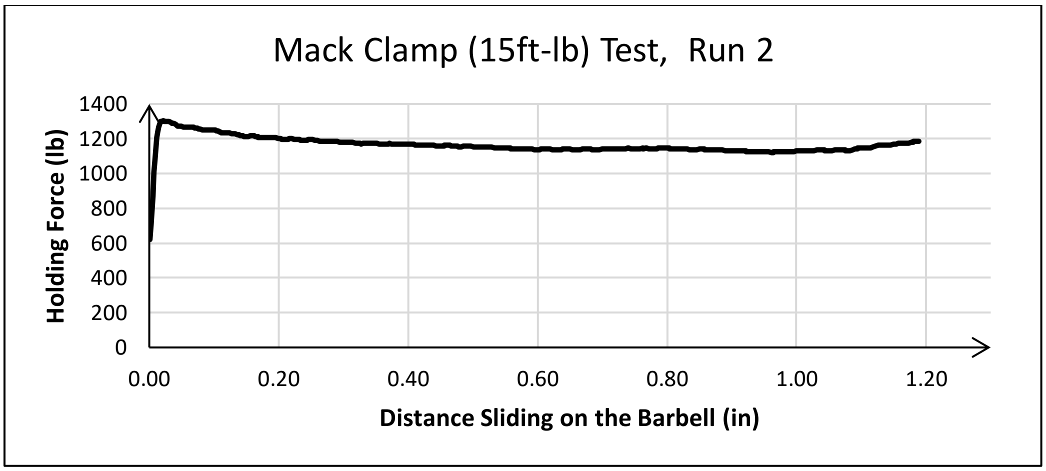
Graph 7 – Mack Clamp 10ft-lb, Run 2



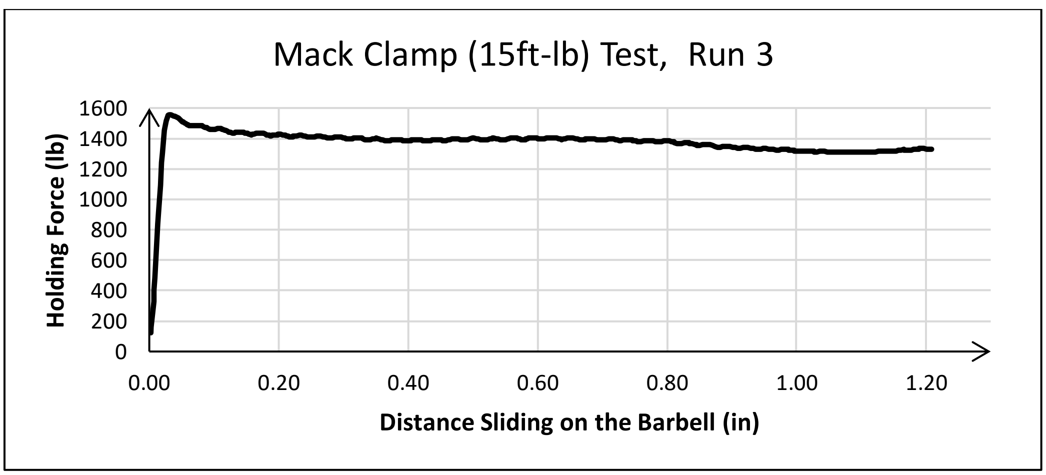
Graph 8 – Mack Clamp 10ft-lb, Run 3



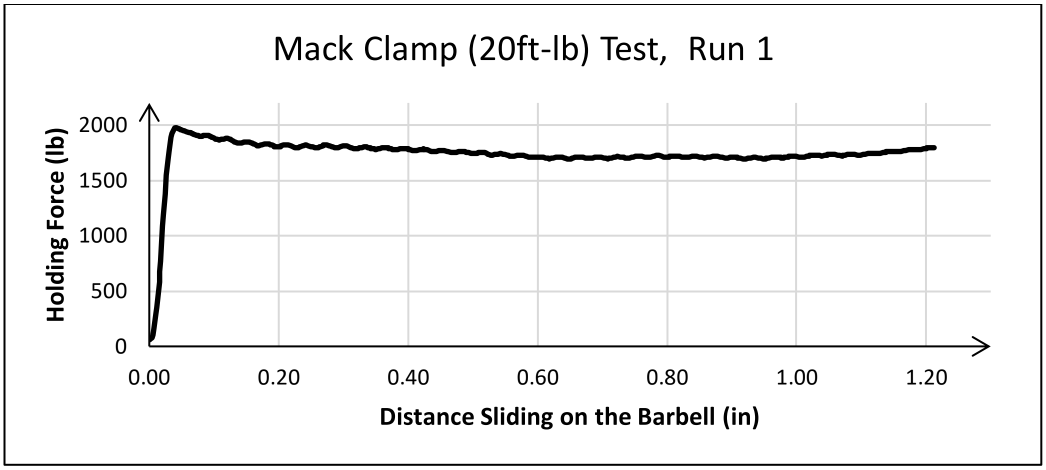
Graph 9– Mack Clamp 15ft-lb, Run 1



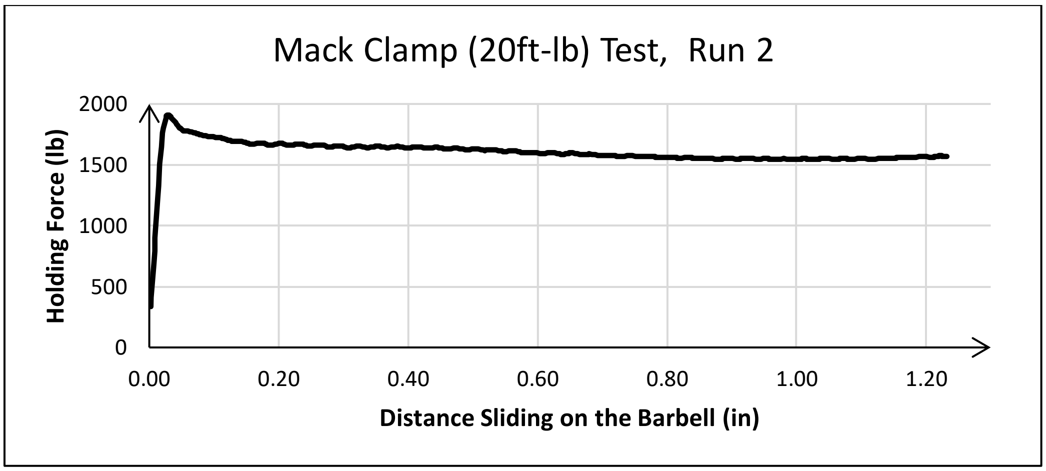
Graph 10– Mack Clamp 15ft-lb, Run 2



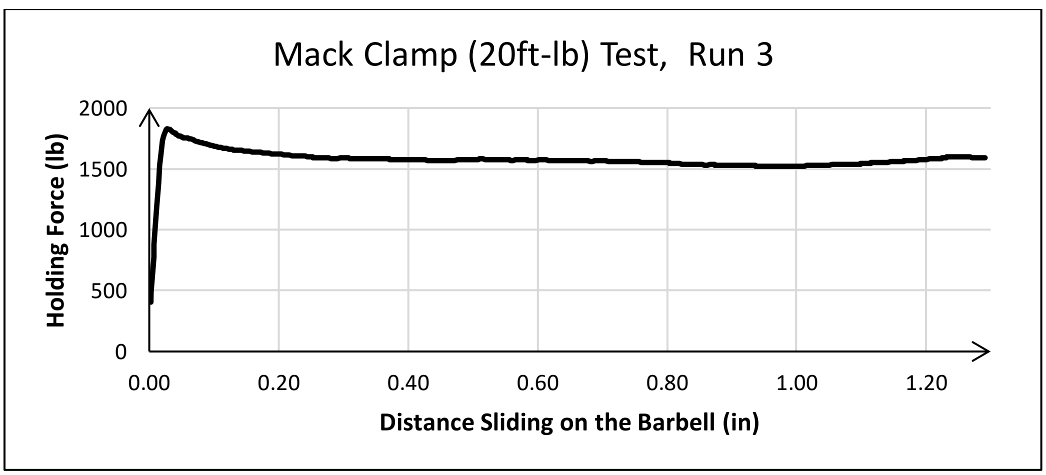
Graph 11– Mack Clamp 15ft-lb, Run 3



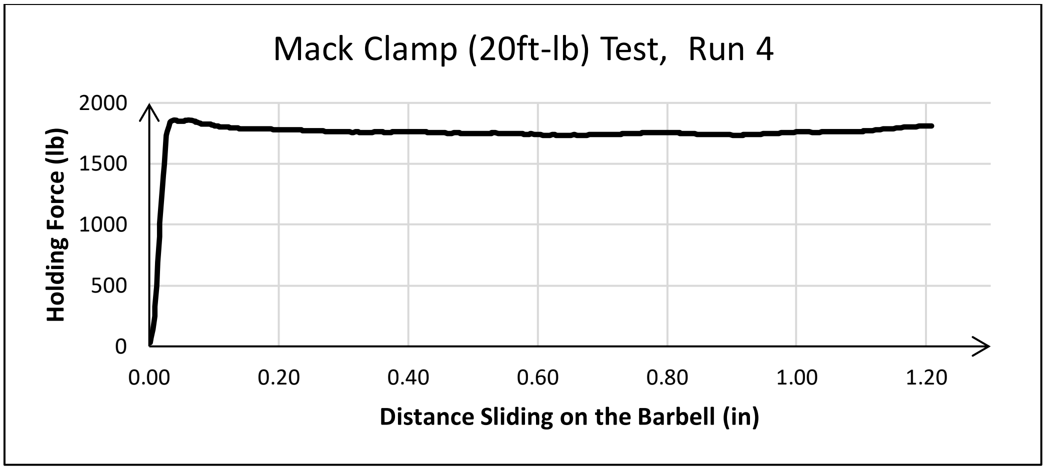
Graph 12– Mack Clamp 20ft-lb, Run 1



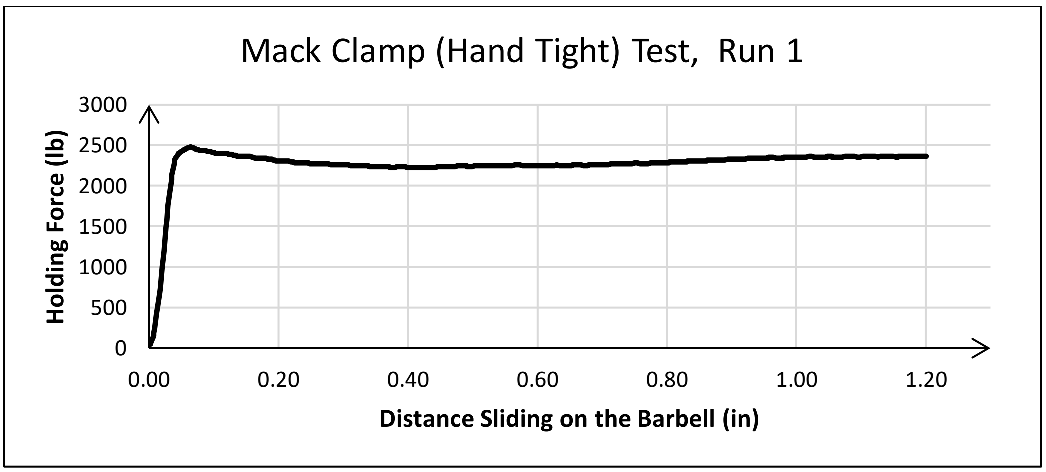
Graph 13– Mack Clamp 20ft-lb, Run 2



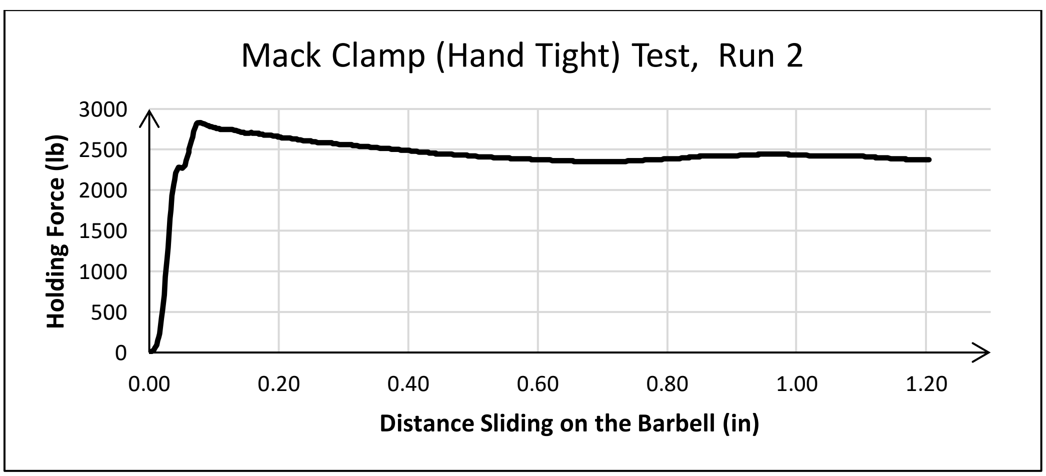
Graph 14– Mack Clamp 20ft-lb, Run 3



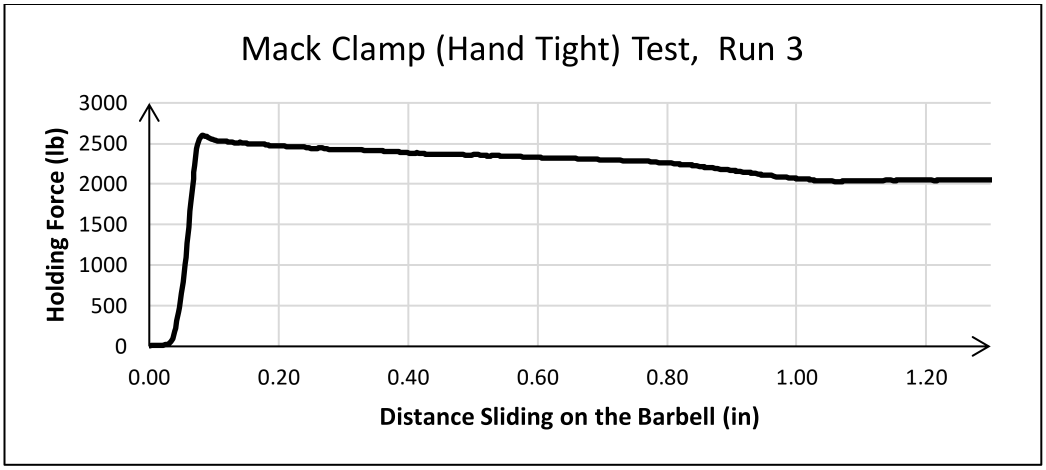
Graph 15– Mack Clamp 20ft-lb, Run 4



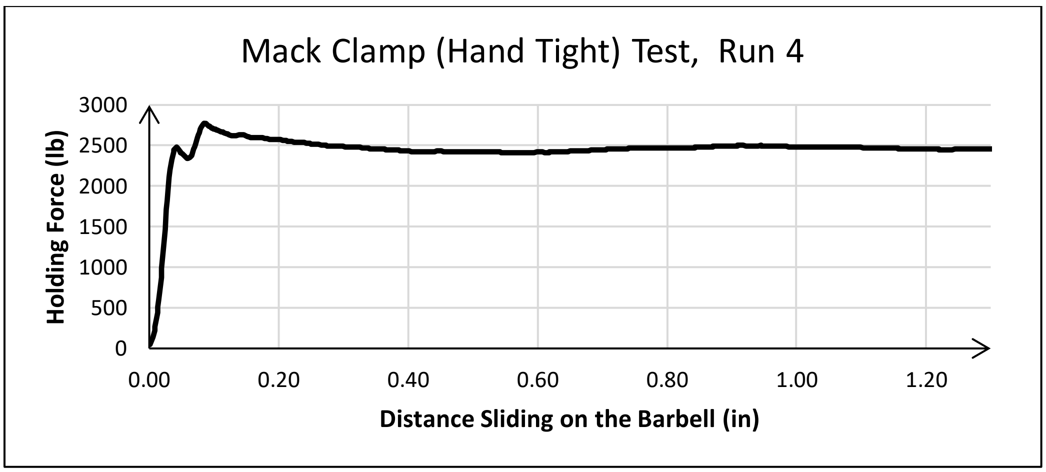
Graph 16– Mack Clamp (Hand Tight), Run 1



Graph 17– Mack Clamp (Hand Tight), Run 2



Graph 18– Mack Clamp (Hand Tight), Run 3



Graph 19– Mack Clamp (Hand Tight), Run 4

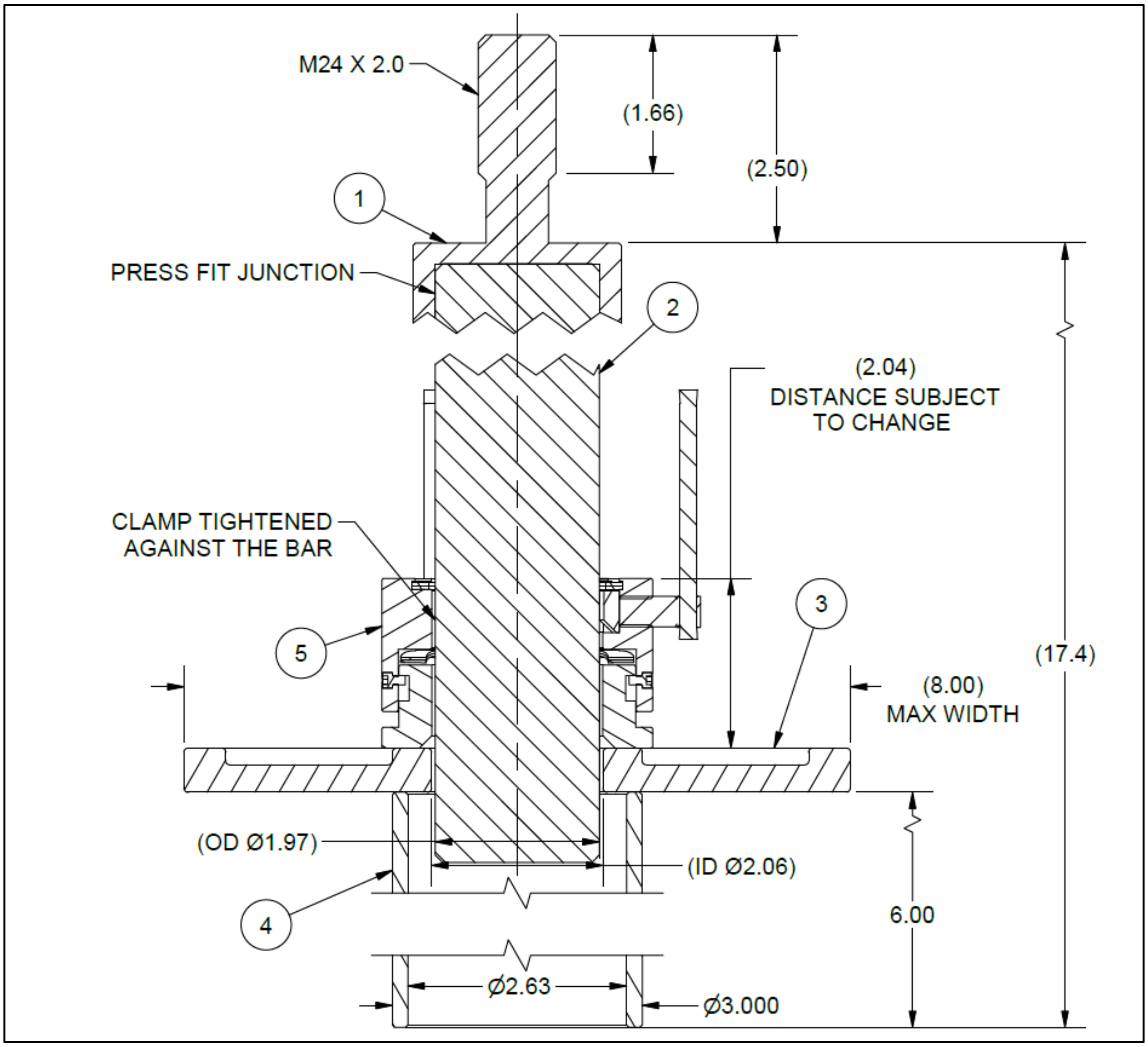


Figure 20. Weight Plate Retention Collar Testing Setup

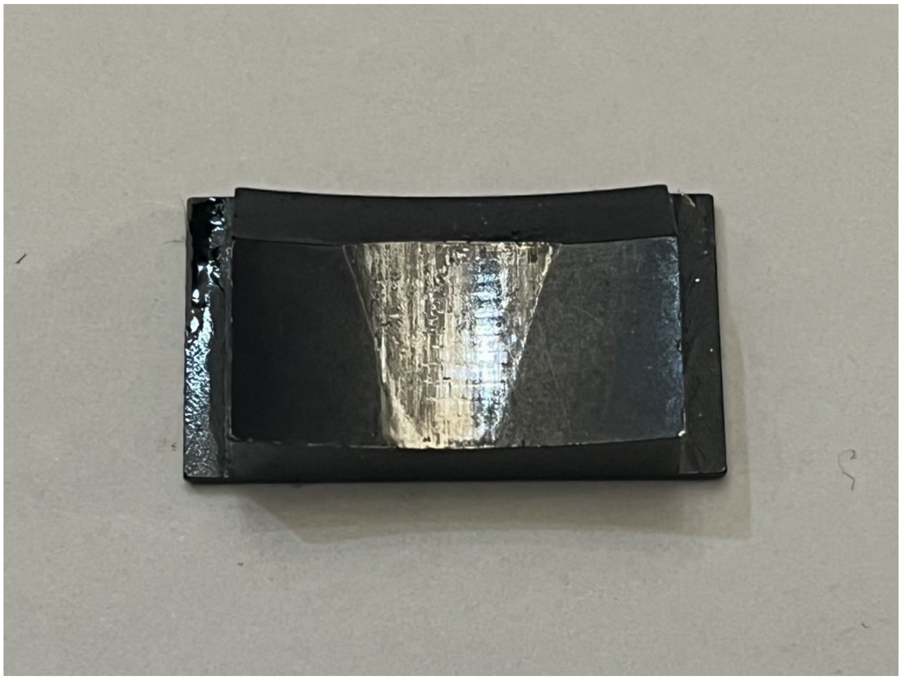


Figure 21. Contact Patch Closeup Post Testing

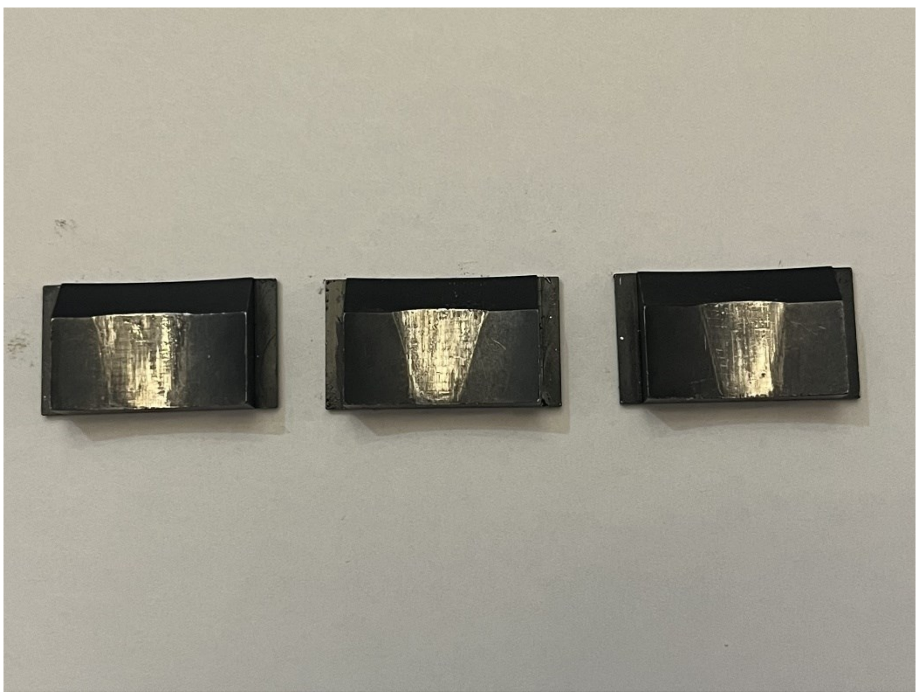


Figure 22. All three Contact Patches post testing

Appendix B: Mack Clamp Illustrations

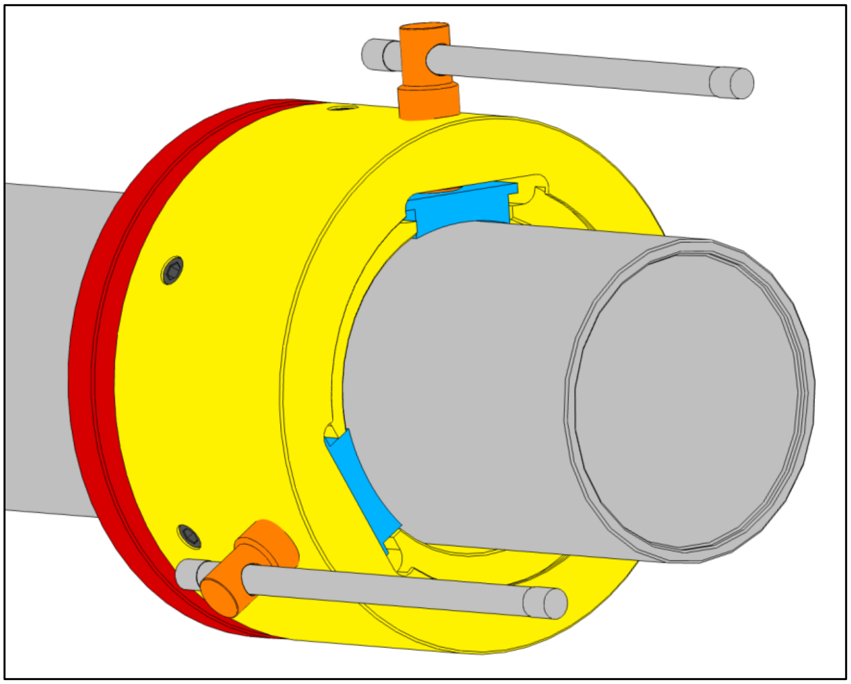


Figure 23. Mack Clamp Tightened onto a barbell sleeve

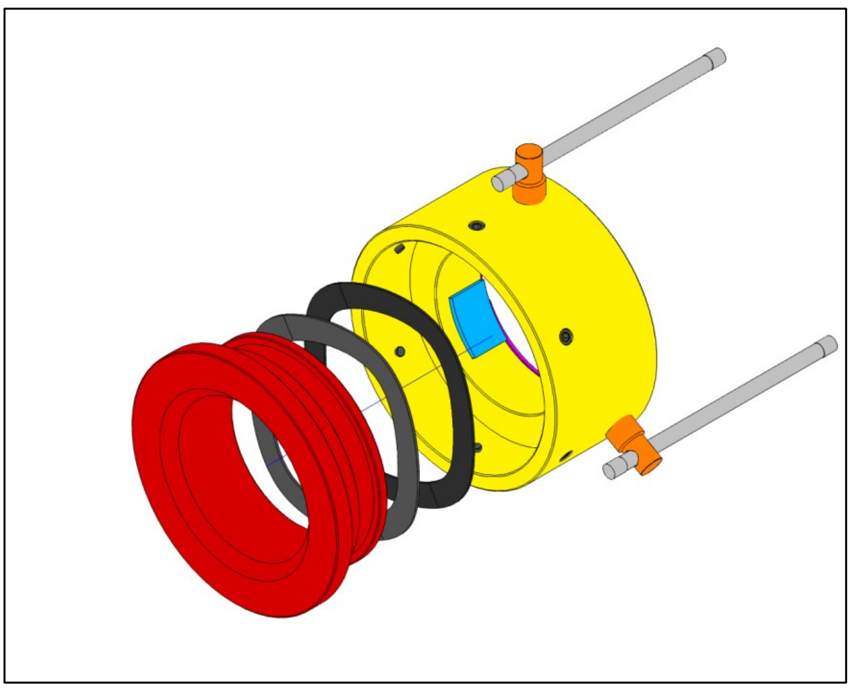


Figure 24.Mack Clamp Dynamic Shock Absorption system

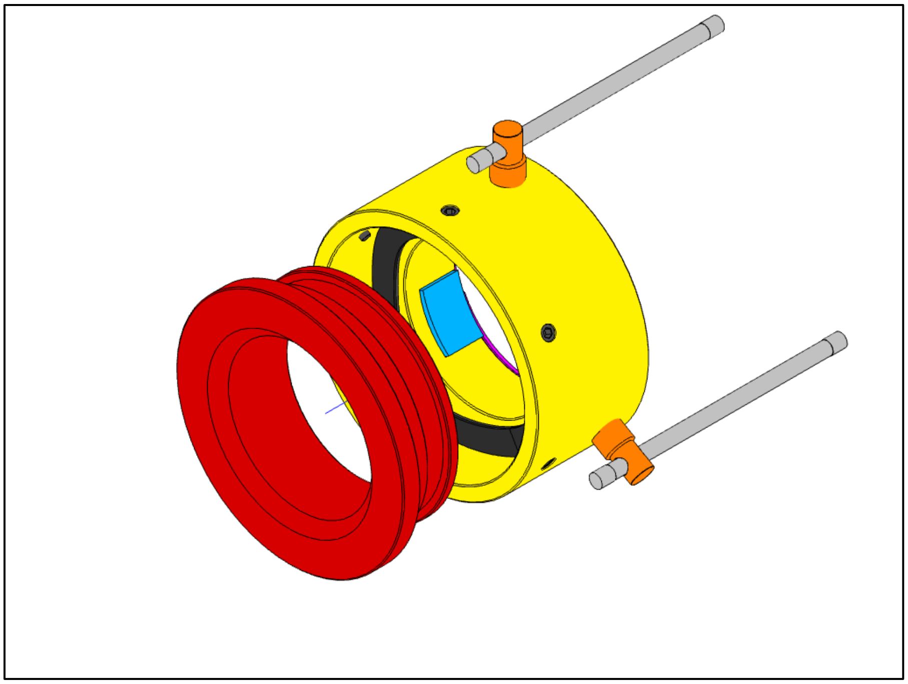


Figure 25. Mack Clamp Rotational Degree of Freedom

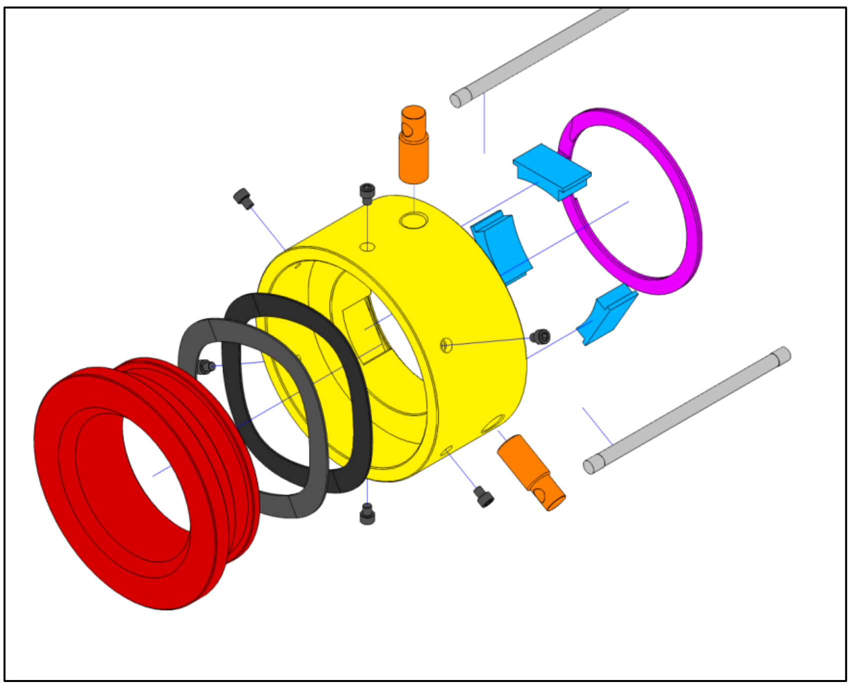


Figure 26. Mack Clamp Explode View