Static Pullout Strength of Power Actuated Fasteners in Steel: State-of-the-Art Review

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Power-actuated fasteners (PAFs) are high strength nails used for making attachments to steel or concrete. PAFs driven into steel are the subject of this paper. PAFs are driven into steel using either powder-actuated or pneumatically driven tools and provide an alternative to more conventional fasteners such as welds, bolts, and screws. Power-actuated fastening systems for steel have been available for over 50 years. However, relatively little research information has been published on this fastening system in journals or in other engineering research and design literature.

The purpose of this paper is to provide an overview of power-actuated fastening for steel and to provide a state of the art review on the static pullout strength of individual power-actuated fasteners in steel. Much of the past research and testing information on PAFs is contained in unpublished or proprietary research or test reports that are not widely or easily available to researchers and engineers. This lack of public domain literature on PAFs for steel is the primary motivation for this paper, which summarizes test data that is not otherwise easily available.

This paper begins with an overview and brief history of power-actuated fastening technology for steel, with background information on typical fasteners, installation tools and applications. Anchoring mechanisms for PAFs in steel are then briefly discussed. Following this is a summary of data on the strength of individual fasteners subject to static loading in tension. Several key variables that affect fastener pullout strength will be discussed, including embedment depth, base steel thickness and strength, fastener diameter, fastener knurling, and other factors.

While the focus of this paper is the behavior of PAFs under static tension loading, significant data and information is also available for other loading cases, such as PAFs subject to fatigue loading in tension, static or fatigue loading in shear, and other cases. However, the scope of this paper is limited to the behavior of PAFs under static tension only.

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BACKGROUND ON PAFS IN STEEL

Power-actuated fasteners (PAFs) can be driven either by an explosive charge or by compressed air into concrete, masonry, steel or other materials. The focus of this paper is the application of PAFs in steel base materials. A key characteristic of this fastening system is that no hole is predrilled into the base material. When the fastener is driven into steel, it forms its own hole and displaces the steel; somewhat analogous to driving a conventional nail into wood. To enable that process, PAFs have a very high strength, up to 320 ksi. The diameters of PAFs typically vary in the range of about 0.1 to 0.2 in. The fasteners are available in a variety of forms for particular applications. Various names have been applied to these fasteners in manufacturers' and other literature. Most common is the term "powder-actuated" fastener, referring to the case where the fastener is driven by an explosive charge. When driven by compressed air, they are sometimes referred to as "pneumatically-driven" fasteners. They are also referred to as nails, studs, or shot-fired pins. In this paper, the term "power-actuated" fastener is taken to include both powder-actuated and pneumatically-driven fasteners. The same convention has been adopted by ASTM (1995).

History

The history of PAFs is not well documented, although some historical background has been published by manufacturers of these systems (Hilti, 1995; Ramset, 1969) and by others (Schillings, 1970). The development of the first powder-actuated nailing device has been attributed to Robert Temple in the early 1900s. The first US patent for a powder-actuated tool appears to have been granted to Temple in 1921 (US Patent No. 1365869). An early application cited for powder-actuated tools was to locate submarines during World War I. A diver could drive a nail into the hull of a submarine and run a signal line to the surface to mark the submarine's location. An additional application was for salvaging or repairing ships, wherein a diver could attach steel patches over holes in a ship's hull by the use of power-actuated fasteners. PAFs are still used for this purpose today. Early versions of powder-actuated tools were also used as cattle stunners in slaughterhouses. For this application the tool did not utilize a projectile but rather contained a captive piston that was driven by a powder charge.

The use of powder-actuated tools for construction applications appears to have been developed by several manufacturers in Europe and the US in the 1940s. According to current standards, the early powder-actuated tools would be classified as high velocity tools. With these systems, the powder charge acts directly on the nail and the combustion energy is transferred to the nail as kinetic energy. Fasteners fired from high velocity tools can achieve velocities over 1,000 ft/sec and can penetrate steel plates several inches in thickness. Clearly fasteners driven at these high velocities can present a hazard to workers on the job site. In the 1950s, safer alternative systems of driving fasteners were developed. One of these alternatives was hammer driven systems without a powder charge, which utilized a guide tool and a common hammer. These manual systems were suitable for driving fasteners primarily into concrete but also into relatively thin steel plates less than about $^1/_4$ in. in thickness. Also in the late 1950s, low velocity powder-actuated tools became available as a safe alternative to high velocity tools. These systems limit fastener velocity to about 330 ft/sec. A review of manufacturers' literature indicates that commercial production of high velocity tools was discontinued in the 1980s. Currently, only low velocity powder actuated tools are commercially available for construction applications.

In the 1980s, pneumatic tools in a comparable energy range as powder tools were developed. These tools utilize compressed air to drive the fastener and require an external air compressor. Pneumatic tools appear to have been developed primarily to permit faster installation in highly repetitive applications such as fastening steel roof deck.

Installation Tools

As described above, there are two primary types of tools for installation of PAFs: powder-actuated tools and pneumatic tools. Powder-actuated tools have a long history in construction, while the introduction of high-energy pneumatic tools for this application has been relatively recent.

Powder-actuated tools use a *power load* (sometimes also referred to as a *powder load*) of explosive powder to drive the fastener. The power loads are usually provided in a crimped case and are supplied either as individual cartridges or as multiple power loads mounted on strips or disks. In the US, ANSI A10.3 (ANSI, 1995) standardizes coding of power loads. Twelve different power levels are defined, with Level 1 being the lowest, and Level 12 being the highest. ANSI A10.3 also establishes a standard color coding system for power loads, with a color associated with each power level. Power loads are available in different caliber sizes for different tools. Each manufacturer of powder-actuated tools normally supplies their own line of power loads for use with their tools.

Classifications for powder-actuated tools are provided by the ANSI A10.3 (ANSI, 1995) and by the Powder Actuated Tool Manufacturers Institute (Powder, 1991). According to these sources, powder-actuated tools are classified as either direct or indirect acting, and then are further classified as low, medium or high velocity tools.

In a direct acting tool, the expanding gas of the power load acts directly on the fastener. In the case of an indirect acting tool, the expanding gas of the power load propels a captive piston, which in turn drives the fastener. Tools are further classified as high, medium and low velocity according to ANSI A10.3. In high velocity tools, the speed of the fastener leaving the tool is greater than 490 ft/sec. For medium velocity tools, the fastener speed is in the range of 330 to 490 ft/sec, and for low velocity tools, fastener speed does not exceed 330 ft/sec.

Most powder-actuated tools are classified as either high velocity or low velocity and, in general, high velocity tools are direct acting and low velocity tools are indirect acting. High velocity direct acting tools dominated the industry in the early development of powder-actuated systems from the 1940's through the 1960's. Starting in the late 1950s, low velocity indirect acting piston driven tools were developed as a safe alternative to high velocity tools. Only low velocity tools are now commercially available for construction applications.

Literature (Hilti, 1995; Ramset, 1969) indicates that a major reason behind the development of low velocity tools was safety. Fasteners driven by high velocity tools can develop speeds as high as 2000 ft/sec and can cause serious injury if the fastener ricochets, misses the base material, or penetrates and passes through the base material. In the case of the low velocity tools, about 95 percent of the power load's energy is contained in the captive piston, resulting in less energy imparted to the fastener and dramatically reduced fastener velocity.

Safety standards for powder-actuated tools are contained in ANSI A10.3 and in OSHA regulations (OSHA, 1993 and 1996). These standards cover a variety of issues, including classification of tools, standardization of power loads, tool safety mechanisms and warning labels, and safe operating practices. These safety standards also require operators of powder-actuated tools to receive training and to become certified by passing an examination. Operators are required to carry a certification card whenever they use a powder-actuated tool. A number of publications cover safety-related topics and recommendations for safe use of powder-actuated fastening tools (Bauer, 1975; NIOSH, 1978a and 1978b; and National Safety Council, 1985; Powder Actuated Tool Manufacturers Institute, 1991; Hilti, 2000; Van Allman, 1992).

Applications for Power-Actuated Fastening to Steel

Typical current applications of power-actuated fastening to steel are cited in manufacturers' literature and in a recent construction industry survey (Glaser and Engelhardt, 1994). One of the most commonly cited applications is the attachment of steel roof deck to steel beams or open web steel joists. In this application, the PAF is driven through the steel decking into the underlying beam or joist. In current US practice, steel roof decking is more commonly fastened using puddle welds or screws, although PAFs appear to be seeing increased use as a substitute for welds or screws (Glaser and Engelhardt, 1994). Interestingly, PAFs represent the dominant method for attaching roof decking to steel members in Europe, where puddle welding is seldom used.

Similar to the attachment of steel roof deck, PAFs can also be used for attaching steel floor decking or wall cladding to steel members. At least one PAF manufacturer has also developed a cold-formed shear connector that can be used in lieu of welded shear studs for composite beam construction (Crisinel, 1990). In this application, the cold-formed shear connector is fastened to the underlying steel beam or joist by means of PAFs.

Another common application of PAFs is for the attachment of a variety of mechanical or other non-structural items to steel members. This includes the attachment of items such as electrical conduit and junction boxes, HVAC duct supports, pipe hangers, suspended ceiling supports, fire sprinkler supports, etc. PAFs are also used for attaching wood members to steel, for attaching light gage metal studs to steel members, and for attaching metal floor grating to steel beams in industrial structures.

Other unique applications reported in the literature include the use of PAFs to attach noise insulation panels to steel members on a railway bridge (Seeger and Hanel, 1975), the use of PAFs for connecting tubular steel members (Packer, 1996; Kosteski, Packer, and Lecce, 2000), and the use of PAFs as shear connectors for developing composite action in concrete-filled steel tubes (Tschemmernegg and Beck, 1998). Recently, PAFs have also been used to attach metal stay-in-place form deck to steel bridge girders in the US.

Fastener Characteristics

The strength, dimensions, designations and other characteristics of PAFs are not standardized, as is the case, for example, with high strength bolts. Rather, each PAF manufacturer produces its own proprietary line of fasteners (Hilti, 1996; ITW Ramset/Red Head, 2000; Pneutek, 1992; Power Fasteners, 2000; Hilti, 2001). A large number of fasteners are available with different configurations, dimensions and other features for specific applications. Nonetheless, there are some general similarities among the type of fasteners available from different manufacturers.

Figure 1 illustrates some typical power-actuated fasteners. PAFs can be divided into two broad categories: drive pins and threaded studs. Drive pins are nail-like fasteners used to attach materials or other objects to a steel base material. Drive pins can be used to attach items such as steel decking, wood members, metal studs, insulation, conduit clips, etc. to a steel member. Figures 1 (a) to (d) illustrate some typical general-purpose drive pins. Figures 1(e) and (f) show drive pins specifically intended for attachment of steel deck to steel members. Most manufacturers of PAFs offer fasteners specially designed for attachment of steel decking. Drive pins are driven though the fastened material, such as steel decking, into the underlying steel base material. Normally, no hole is predrilled in either the fastened material or in the base steel.

The second major category of power-actuated fasteners is the threaded stud. Figures 1(g) and (h) show examples. The lower shank portion of the stud is driven into the base steel member. The upper portion of the fastener consists of an enlarged threaded head. Objects can be attached to the threaded head using a nut.

A wide variety of different drive pins and threaded studs are available from PAF manufacturers. Typical diameters of the shank portion driven into the base material are in the range of about 0.1 to 0.2 in. The overall length of the fasteners varies from about 0.4 to 4.75 in. depending on the type of fastener and its intended application.

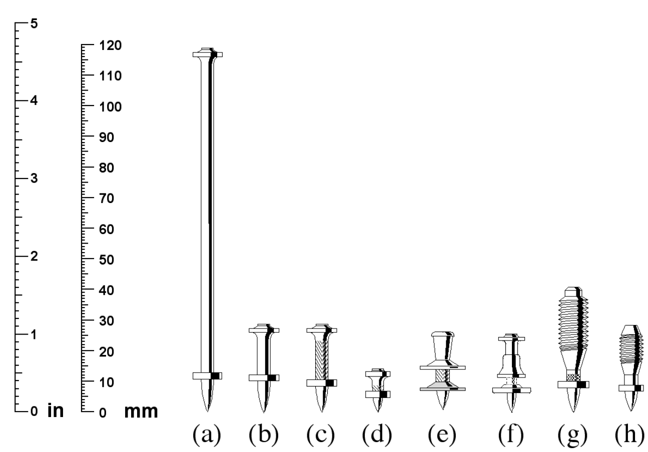


Fig. 1. Typical power actuated fasteners.

As can be seen in Figure 1, drive pins are typically provided with an enlarged head and sometimes, in addition, with a washer near the top of the fastener. The washer or enlarged head serve several purposes. They maintain the alignment of the fastener in the barrel of the installation tool, they may serve to prevent the fastener from penetrating too far into softer materials such as wood, they provide a large bearing area to prevent pullover failures of the fastened material, and can also be used to control the depth of penetration of the fastener into the base material. In some designs, a bell shaped washer is compressed during the driving process, and subsequently provides a clamping pressure on the fastened material. Additionally, plastic or metal washers are often provided near the driving tip of the fastener. These washers are used to center and align the fastener in the barrel of the installation tool, and may also serve the additional functions as described above.

The portion of the fastener shank driven into the base steel can have a variety of characteristics. The lower portion of the shank is tapered to a sharp point to facilitate penetration of the fastener through the fastened material and into the base material. The specific geometry and surface finish of the driving tip varies among fasteners and manufacturers, and details are usually treated as proprietary information. The portion of the shank above the driving tip is typically cylindrical in shape, with a constant diameter. Some fasteners, however, are provided with a slight taper along the full length of the shank. The portion of the shank above the driving tip can be either smooth or knurled. Knurled shanks are generally intended to improve anchoring capacity of zinc-plated fasteners in steel.

Manufacturers' literature reports that most PAFs are made of heat-treated steel that is subsequently provided with a thin zinc coating for temporary corrosion protection during assembly. For permanent structural applications, zinc-coated carbon steel fasteners are recommended only for indoor use in a noncorrosive environment. Details of the fastener materials and heat treatment are considered proprietary among manufacturers, although most report that the fastener is heat treated to provide hardness on the Rockwell C scale of approximately HRC 54 to 58. This corresponds to an ultimate tensile strength in the range of approximately 275 to 320 ksi (DIN, 2000). In addition to zinc-coated heat-treated steel fasteners, stainless steel fasteners are also available.

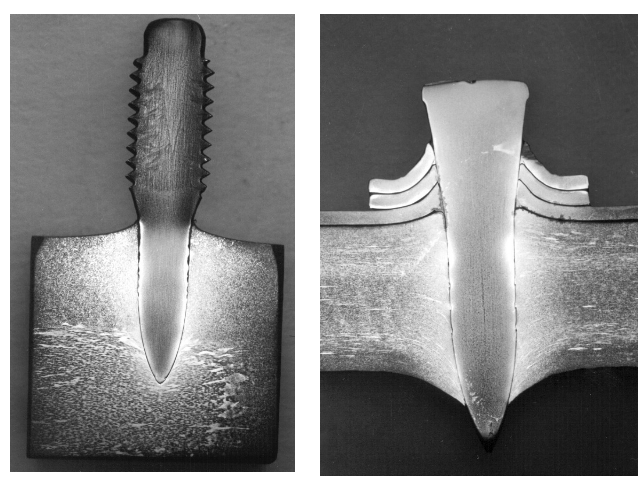
PAF manufacturers typically supply the fastener, installation tool and power loads as a complete system. Recommendations are provided in manufacturers' literature on the type of fastener, tool, and power load appropriate for specific applications. Recommendations are also normally provided on the maximum thickness and strength of base steel that can be used with a particular fastener so that the PAF can be driven into the base steel without breaking or otherwise damaging the fastener. An example of such application limits can be found in Hilti (2000). Such recommendations are generally developed through testing. Numerical simulations of the driving process for PAFs have also been recently reported (Bartelt, Ammann, and Anderheggen, 1994).

FASTENER ANCHORING MECHANISMS IN STEEL

Figure 2 shows photos of PAFs driven into steel plates. In each case, the fastener and steel plate were sectioned along the center of the fastener. Figure 2(a) shows the case where the fastener tip penetrates the steel base material, whereas Figure 2(b) shows a case where the fastener tip is embedded in the steel base material. In both cases, the fastener is held in the steel base material and provides resistance to pullout under tension or shear loading.

A review of the literature revealed no publications providing either analytical models or test data that quantify the anchoring mechanisms of a PAF in steel. However, literature from PAF manufacturers (Hilti, 1996; Power Fasteners, 2000; Hilti, 2000) and other literature (Glaser and Engelhardt, 1994; Powder Actuated Tool Manufacturers' Institute, 1991) provide general descriptions of the mechanisms that contribute to the pullout capacity of PAFs driven into steel. Additional discussion on anchoring mechanisms is also provided by Zobel (1968). Four mechanisms are identified: friction, mechanical interlock, fusion, and soldering. Descriptions of these mechanisms as provided in the literature are briefly discussed below.

When a PAF is driven into steel, the steel is displaced, and subsequently provides a clamping pressure on the surface of the fastener. This clamping pressure permits the development of friction at the fastener/base steel interface, which provides resistance to fastener pullout. When the fas-



(a) (b)

Fig. 2. Power actuated fasteners embedded in steel plates.

tener surface is knurled, an additional anchoring mechanism identified for PAFs driven into steel is mechanical interlock or keying between the fastener and the base steel. Reportedly, the base steel flows into the grooves on the fastener surface to provide mechanical interlock. This interlock is also reported to increase the resistance of the fastener to rotation in the base steel when torque is applied for tightening a nut on a threaded stud.

Owing to friction between the fastener and the base metal, high temperatures are developed at the fastener surface during the driving process. In the tip region of the fastener the temperatures exceed 1800°F resulting in partial fusion of the tip with the base metal. Soldering of the zinc layer occurs along the rest of the interface where less heat is developed.

Data to verify and quantify the relative contributions of these four anchoring mechanisms for PAFs driven into steel was not found in published public domain literature. Manufacturers' literature (Hilti, 2000) indicates that keying is of specific importance for anchorage of zinc-plated knurled fasteners in steel. Clamping combined with keying represents the dominating mechanism when the fastener completely penetrates the base steel (Figure 2a), as fusion and soldering mechanisms primarily develop in the region of the embedded point (Figure 2b).

BEHAVIOR OF PAFS IN TENSION

A common loading case for PAFs is the case where the fastener is subject to tensile loading. The load may be applied directly to the fastener, as may be the case with a threaded stud. Alternatively, the load may be applied to the fastener through the fastened material. For example, steel roof decking attached to a steel beam by PAFs may be subjected to uplift forces due to wind. The uplift forces on the steel deck will result in a tension load on the fastener.

There are several possible failure modes for PAF installations subjected to tension. Failure may occur by pullout of the fastener from the base material. Alternatively, the fastener itself may fracture in tension. However, due to the very high strength steel used for PAFs, fracture of the fastener rarely occurs prior to pullout. Consequently, pullout capacity normally governs the maximum tension force that can be applied to a PAF.

When a PAF is used to hold down steel decking materials, pullover failures can occur in the fastened material, i.e., the fastened material is pulled over the PAF. This failure mode involves fracture or tearing of the fastened material, and depends largely on the thickness and strength of the fastened material, as well as on the bearing area and the design of the PAF washer on the fastened material. In some cases, failure can also occur by pullover of the PAF washer, representing a failure of the washer.

The primary failure mode in tension for the fastener, as opposed to the fastened material, is pullout of the fastener from the base material. The remainder of this paper provides an overview of the pullout capacity of PAFs in steel subject to static tension loads. Included is a brief discussion of test methods, load-deflection behavior, and factors affecting pullout capacity.

Test Methods

In the US, testing of PAFs in tension and shear is covered by ASTM E1190-95 (ASTM, 1995), which addresses PAFs driven into concrete, masonry or steel. In Europe, testing recommendations are provided by ECCS (1983) and by a draft of the DIN 18807 Part 4 (DIN, 1996). For determining tension capacity, a PAF can be tested by applying tension loads to a folded piece of sheet steel that is fastened to a steel base material with the PAF. This approach can be used for determining either pullout or pullover failure loads. By using a sufficiently thick piece of sheet steel, pullover failure is avoided, and the setup can be used to evaluate fastener pullout capacity. Alternatively, tension force can be applied directly to the fastener by connecting a loading device to the threads of a threaded stud, or by specialized grips that clamp the head of a drive pin. Multiple tests are typically conducted to obtain sufficient data for statistical analysis of fastener strength. The number of required tests is specified in the testing standards noted above. Other requirements for the number of required tests and the subsequent statistical analysis of fastener strength data can also be based on the requirements of code approval bodies or based on procedures developed by the PAF manufacturer. An example of the statistical treatment of fastener test data to derive design values can be found in the *DX Fastening Technology Manual* (Hilti, 1996).

Load-Deflection Response for Fastener Pullout

Figure 3 shows an example of the load-deflection response from a fastener pullout test (Tschemmernegg, 1997). The vertical axis in this plot represents the tension load on the fastener, and the horizontal axis gives the displacement of the fastener measured relative to the base material. As indicated by the plot, pullout behavior of PAFs in steel is not a ductile process, i.e., after the peak strength is achieved, the tension force supported by the fastener drops rapidly. When pullout tests are conducted on PAFs, typically only the peak load on the fastener is measured and reported. Consequently, little load-deflection data of the type shown in Figure 3 is available in published literature.

Factors Affecting Pullout Capacity

A review of literature (Hilti, 1996; Glaser and Engelhardt, 1994; Powder Actuated Tool Manufacturers' Institute, 1991; Ramset, 1969; Hilti, 2000) indicates that a number of factors may affect the pullout capacity of PAFs in steel. These include the embedment depth of the fastener, the base steel thickness, the base steel strength, the diameter of the fastener, knurling of the fastener, fastener zinc coating thickness, base steel stress, and other factors.

Data on fastener pullout capacity is available primarily in manufacturers' literature (Hilti, 1996; ITW Ramset/Red Head, 2000; Pneutek, 1992; Powers Fasteners, 2000; Hilti, 2001) and from reports issued by product certification agencies such as the ICBO Evaluation Service, for example ICBO (1995). However, the data presented in these sources is generally not sufficient to identify and isolate the effect of various parameters on pullout capacity. In some cases, not all of the important test conditions that may affect pullout capacity (embedment depth, etc.) are clearly identified. Further, these sources generally report allowable working loads on the fasteners. The actual measured capacities are generally not reported. As a result, fastener strength data available in published literature is generally insufficient to clearly identify the factors affecting the pullout capacity of PAFs in steel.

To allow for better identification of the influence of different variables on fastener pullout capacity, data from unpublished test reports was made available to the writers by Hilti Corporation. These reports contained sufficient detail on test conditions to isolate the effects of several different variables on pullout capacity. This data is presented in the following sections. Note that the fastener designations indicated in Figure 3 and in Figures 5 to 11 correspond to designations for fasteners produced by Hilti Corporation. While the actual values of pullout capacity presented below are applicable only to the specific fasteners that were tested, the general trends in strength variation should be representative for a broad range of PAFs.

Figure 4 illustrates the definitions of several terms that will be used in the following sections that relate to a PAF driven into a steel base material. Figure 4a illustrates the case where the PAF tip fully penetrates the base steel; Figure 4b shows the case where the PAF tip remains embedded within the base steel.

Embedment Depth

A primary variable affecting pullout capacity of PAFs in steel is the *embedment depth,* h_{ef}. Embedment depth is defined as the distance from the surface of the base steel material to the installed tip of the fastener. Even when the fastener tip penetrates through the base steel, as in Figure 4a, the full distance from the surface of the base steel to the fastener tip is included in the embedment depth. Note that the definition of embedment depth is independent of the base steel thickness, as it measures the complete driving distance in the base metal. In PAF literature (Glaser and Engelhardt, 1994), the terms *depth of penetration, driving depth or driving distance* are sometimes used to designate the same variable. However, the term embedment depth and the corresponding symbol h_{ef} are used herein as these are adopted by ASTM E1190-95 (ASTM, 1995). The determination of embedment depth can be accomplished by measuring the *nail head standoff,* h_{nhs}. As shown in Figure 4, the nail head standoff is defined as the distance from the top of the fastener to the surface of the base steel or, if a fastened material is present, to the surface of the fastened material. Nail head standoff is easily measured in the laboratory or in a field installation with simple gages. As long as the material being fastened is in tight contact with the base steel, measuring the nail head standoff provides a convenient means for determining embedment depth. The embedment depth can be computed by subtracting the nail head standoff (plus the thickness of the fastened material, if any) from the total length of the fastener.

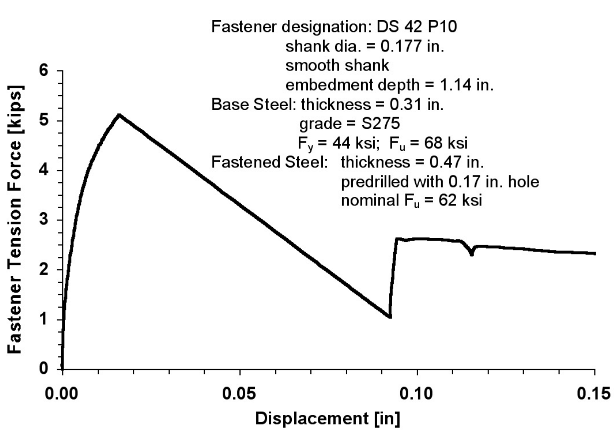


Fig. 3. Load-deflection response for fastener pullout.

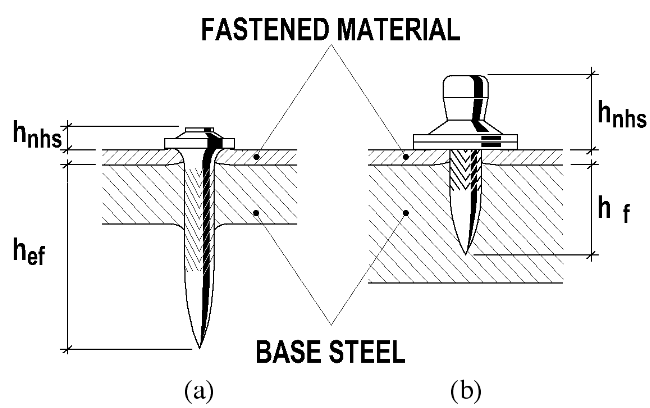


Fig. 4. Definition of terms related to a PAF installed in steel.

Figure 5 presents data on the effect of embedment depth on pullout capacity from Buhri (1989). Each point on this plot represents the result of a single pullout test. Other than embedment depth, other variables remained constant. The same fastener, as indicated in Figure 5, was used for all tests. Further, the same installation tool was used for all tests. Observe that the range of embedment depths in these tests are all less than the base steel thickness of 0.79 in. Consequently, for all tests shown in Figure 5, the tip of the PAF did not penetrate the base steel. Figure 5 illustrates the clear trend that pullout capacity increases with embedment depth.

Figure 6 shows additional data on the influence of embedment depth (Buhri, 1994). Pullout tests were conducted for a 0.16-in. diameter PAF at various embedment depths in 0.24-in.-thick base steel and in 0.79-in.-thick base steel. In the case of the 0.24-in.-thick steel, the PAF fully penetrated the base steel for all embedment depths (embedment depth is greater than 0.24 in. for all tests), whereas for the 0.79-in.-thick steel, the PAF was fully embedded within the base steel for all embedment depths (embedment depth is less than 0.79 in. for all tests). The data in Figure 6 suggests that the pullout capacity for a given PAF with a given embedment depth is not significantly affected by base steel thickness nor by the fact of whether or not the PAF tip penetrates the full thickness of the base steel. Some PAF literature (Powder Actuated Tool Manufacturers' Institute, 1991; Powers Fasteners, 2000) indicates that pullout capacity of a PAF will be reduced if the PAF tip is embedded in the base steel, due to an upward pressure exerted by the base steel on the fastener. The data in Figure 6 does not support this supposition. An explanation for this behavior is the additional

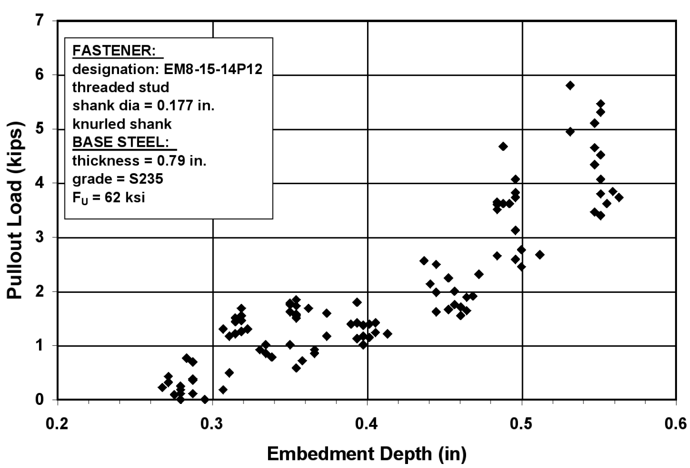


Fig. 5. Variation of pullout capacity with embedment depth: 0.177 in. diameter PAF in 0.79 in. steel.

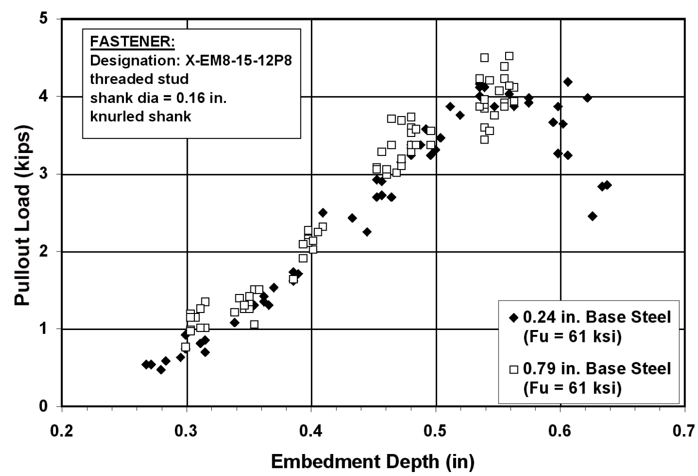


Fig. 6. Variation of pullout capacity with embedment depth: 0.16 in. diameter PAF in 0.24 in. steel and in 0.79 in. steel.

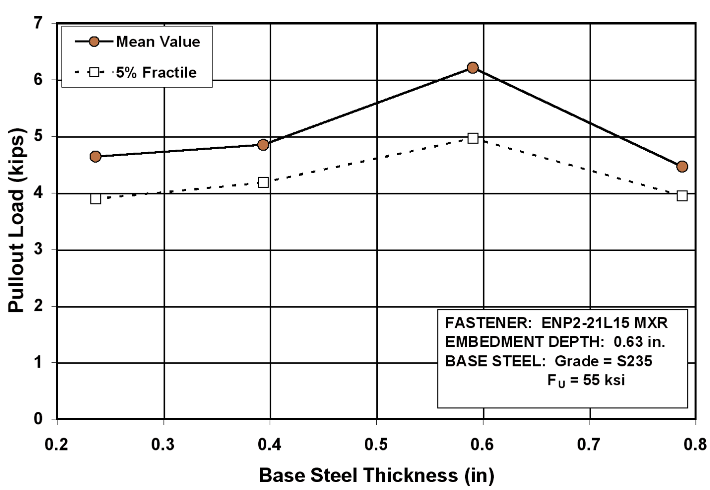


Fig. 7. Variation of pullout capacity with base steel thickness: 0.63 in. constant embedment depth.

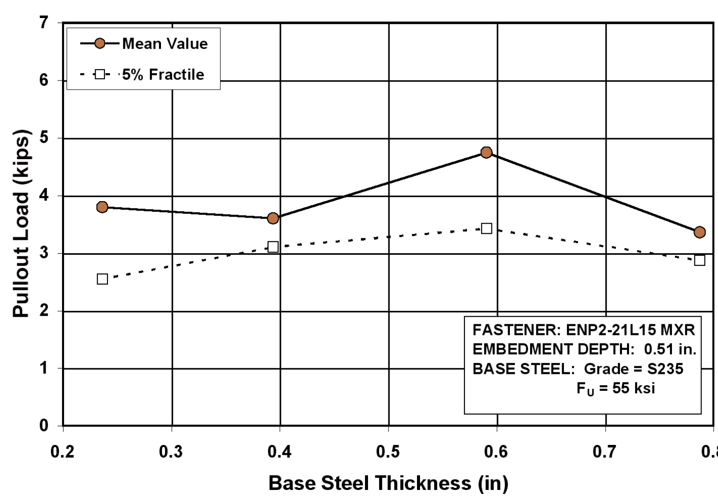


Fig. 8. Variation of pullout capacity with base steel thickness: 0.51 in. constant embedment depth.

fusion mechanism developed in the tip region of the PAF. Literature (Powder Actuated Tool Manufacturers' Institute, 1991) also suggests that fastener pullout capacity is directly related to the total contact area between the fastener and the base material. Again, the data in Figure 6 does not support this supposition. For example, for a 0.47-in. embedment depth, the contact area between fastener and base steel is significantly larger for the 0.79-in.-thick plate than for the 0.24-in.-thick plate. Yet, as indicated in Figure 6, these two cases exhibit nearly the same pullout capacity.

For the 0.24-in.-thick base steel, the data in Figure 6 shows a reduction in pullout capacity at embedment depths greater than about 0.59 in. The PAF used for these tests was a threaded stud, where the length of the shank, measured from the fastener tip to the start of the conical transition to the threaded head, is 0.5 in. The reduction in pullout capacity shown in Figure 6 is likely due to the fact that the conical transition between the shank and the threaded head was driven too far into the base steel, effectively enlarging the top of the hole and thereby reducing the effective contact area between the fastener and the base metal. This phenomenon is sometimes referred to as *overdriving* the fastener (Powder Actuated Tool Manufacturers' Institute, 1991).

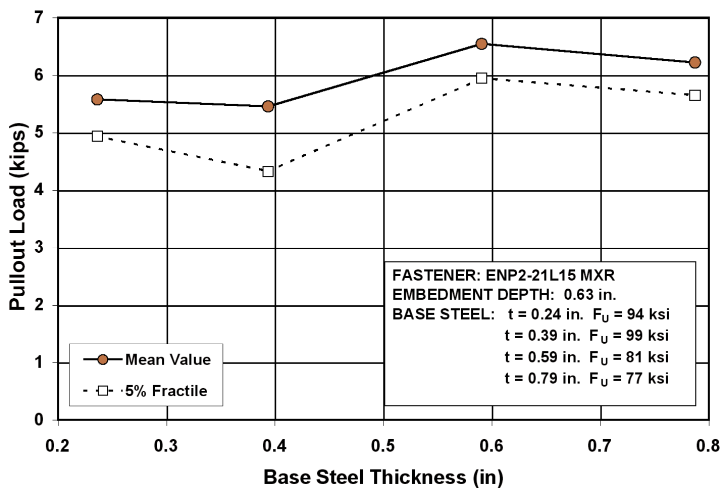


Fig. 9. Variation of pullout capacity with base steel thickness for high-strength steel: 0.63 in. constant embedment depth.

Base Steel Thickness

Data in Figure 6 suggests that for a given embedment depth, base steel thickness may not significantly affect pullout capacity. Additional data on the effect of varying base steel thickness on pullout capacity was obtained from Buhri (1997). Several test series were conducted in which the embedment depth remained constant, but the base steel thickness was varied. Data are plotted in Figures 7 to 9. Each point plotted in these figures is based on 90 pullout tests. For each series of 90 tests, the mean value and the 5 percent-fractile value are plotted in the figures. According to European provisions used for design of steel structures, the 5 percent-fractile represents the value that 95 percent of pullout values exceed with a 75 percent probability.

Figure 7 shows the results of a series of pullout tests in which the embedment depth was kept constant at 0.63 in. With this constant embedment depth, tests were conducted on plate thickness values of 0.24, 0.39, 0.59 and 0.79 inches. The four different values of plate thickness considered in this study were all conducted on plates of the same grade of steel with the same actual tensile strength F_u of 55 ksi. The results in Figure 7 show approximately the same pullout capacity for the 0.24, 0.39 and 0.79 in. thickness base steel materials, and somewhat higher pullout values for the 0.59 in. thick material.

Figure 8 shows similar data for tests on 0.24, 0.39, 0.59 and 0.79 in. thickness base steel materials, but where the embedment depth was kept constant at 0.51 in. The same plate materials were used for these tests as for those plotted

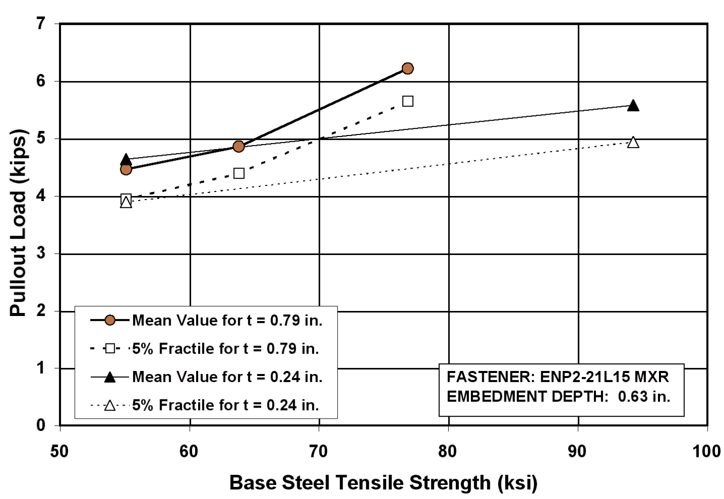


Fig. 10. Variation of pullout capacity with base steel tensile strength.

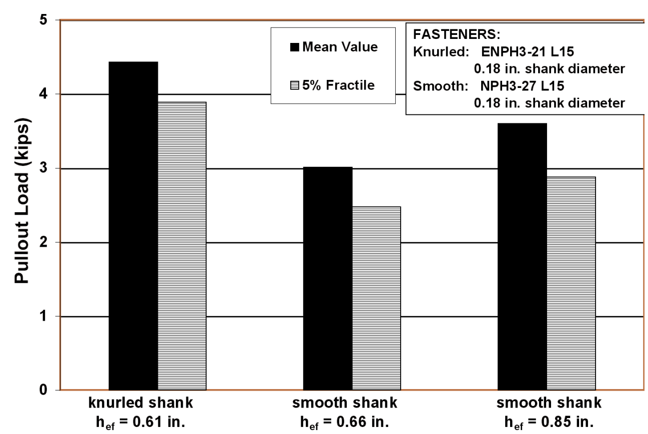


Fig. 11. Effect of knurling on pullout capacity.

in Figure 7. As before, the pullout capacities are similar for most plate thickness values, with somewhat higher pullout capacities recorded for the 0.59-in. plate. The pullout capacities plotted in Figure 8 are lower than those in Figure 7, reflecting the smaller embedment depth.

Owing to the displacement of the base metal during the driving process, a puckered zone at the exit point of the plate is developed resulting in an increase of contact area compared with the original plate thickness. Recently, pullout tests were performed (Buhri, 2000) with fasteners whose tip together with the puckered steel were ground flush with the back surface after nail placement. For 0.24 in. plates it was found that the grinding reduces the pullout value 20 to 40 percent in comparison with normally installed pins. With increasing thickness, this effect reduces and disappears completely for plate thickness beyond 0.39 in.

Based on the data in Figures 7 and 8, it appears that the thickness of the base steel has substantially less influence on pullout capacity than embedment depth. The data suggest the possibility of a small increase in pullout capacity with increasing base steel thickness (assuming constant embedment depth), up to some maximum value, beyond which the pullout capacity decreases. After the fastener point is fully embedded in the base steel, and assuming the embedment depth remains constant, increases in base steel thickness have essentially no effect on pullout capacity (Hoepker, 1995).

Figure 9 plots pullout capacity for plate thickness values of 0.24, 0.39, 0.59 and 0.79 in., with a constant embedment depth of 0.63 in., similar to Figure 7. However, higher strength plates were used for the tests plotted in Figure 9. The actual base steel tensile strength varied with plate thickness, and was in the range of 77 to 99 ksi, as indicated in Figure 9. The trend in pullout capacity as base steel thickness increases is similar to that exhibited in Figure 7, although the variation is less pronounced in Figure 9. This suggests the possibility that base steel thickness has a smaller effect on pullout capacity in higher strength steels. Overall, the data in Figures 7 to 9 suggest that at a constant embedment depth, the base steel thickness does not have a large effect on pullout capacity. This observation is further supported by the data in Figure 6.

PAF manufacturers' literature (Hilti, 1996; Hilti, 2000) suggests that driving PAFs into very thin base steels may pose special problems. Steel base materials with a thickness in the order of the PAF diameter or less fall into this category. In that thickness range, the effect of base metal thickness is pronounced, resulting in smaller pullout values with decreasing base metal thickness. The data shown in Figures 7 to 9 are for fasteners with a 0.18-in. shank diameter. The thinnest base steel included in this data was 0.24 in., which is 1.33 times the fastener diameter. The PAF literature noted above indicates that pullout capacity for typical PAFs can be quite low for thin base steels, even though adequate embedment depths are provided. This issue is of particular significance when PAFs are used to attach steel deck to open web steel joists, as the joist angles are often quite thin. PAF manufacturers offer special fasteners for use in thin base steels. Manufacturers' literature (Hilti, 1996; ITW Ramset/Red Head, 2000; Hilti, 2001) indicates that fasteners are available for use in base steels as thin as 0.12 in. The manufacturers treat the specific fastener design features that permit PAF use in very thin base steels as proprietary information. As an example of the use of PAFs in thin base steels, tests were recently reported on roof subassemblages consisting of steel roof deck and open web steel joists (Engelhardt, Kates, Beck, and Stasney, 2000). The roof deck was attached to the joist top chord angles with PAFs specially designed for use with thin base steels. The top chord angles in these tests were 0.11 in. thick. Satisfactory performance of the PAF attachments was reported in these tests.

Base Steel Strength

Data from Buhri (1997) was also used to examine the effect of base steel tensile strength on pullout capacity. This data is plotted in Figure 10. As before, each point in the plot represents the results of 90 individual pullout tests, with the mean and 5 percent-fractile values shown. For all tests plotted in Figure 10, the same PAF was used, and the embedment depth was held constant at 0.63 in. Tests were conducted on 0.24- and 0.79-in.-thick plates of varying grades of steel to represent a range of material strength values. Shown in Figure 10 are pullout capacities plotted against the actual tensile strength, F_u, of the base steel. The data in Figure 10 clearly suggests that pullout capacity increases as the base steel tensile strength increases, although the magnitude of this effect may vary with base steel thickness.

Fastener Diameter

As described earlier, PAFs are available with shank diameters that are usually in the range of 0.1 to 0.2 in. Information in manufacturers' literature (Hilti, 1996; Powers Fasteners, 2000; Hilti, 2000) and other sources (Beck and Wachmiller, 1985) suggests that pullout capacity increases as the fastener shank diameter increases. No test data was available to the writers in which all variables were kept constant except for fastener diameter to clearly isolate this known effect quantitatively. However, comparing pullout capacities shown in Figure 5 for a 0.18-in.-diameter fastener with that in Figure 6 for a 0.16-in.-diameter fastener indicates somewhat higher pullout capacities for the larger diameter fastener.

Fastener Knurling

PAFs are available with smooth shanks and with knurled shanks. PAF literature (Hilti, 1996; Glaser and Engelhardt, 1994; Powder Actuated Tool Manufacturers' Institute, 1991; Powers Fasteners, 2000; Hilti, 2000) indicates that knurling on the fastener shank is provided to increase pullout capacity in steel. Consequently, knurled fasteners are generally intended for use in steel base materials, whereas smooth shank fasteners are intended for use in concrete or masonry base materials. Smooth shank fasteners, however, can also be used in steel, but require a greater embedment depth than knurled fasteners and therefore typically penetrate the base metal. Owing to the energy limits of tools commonly used in the construction industry, the practical use of smooth shank nails is limited up to a base steel thickness of approximately ½ in.

Data showing the effects of knurling on pullout capacity of PAFs in steel can be derived from Litscher (1989). This data is shown in Figure 11. Three series of tests were conducted. Each series consisted of thirty individual pullout tests, with the mean and 5 percent-fractile values reported in Figure 11. All tests were conducted with PAFs driven into 0.39 in. steel plate with an actual tensile strength of 77 ksi. For each test series, the embedment depth remained constant at the values shown in Figure 11. For both the smooth and knurled shank fasteners used in these tests, the fastener diameter was 0.18 in. The data shown in Figure 11 indicate that knurling does clearly increase pullout capacity. The embedment depth of the knurled fasteners was less than that of the smooth shank fasteners. Yet, the knurled fasteners exhibited significantly higher pullout capacities.

Other Factors

Several other factors are cited in the literature as potentially affecting pullout capacity of PAFs in steel. One of these factors is the thickness of zinc coating on PAFs. Recent literature (Hilti, 2000) presents data showing that an increase in zinc coating thickness results in a decrease in pullout capacity. Other literature (Hilti, 1996) shows higher pullout capacities for uncoated stainless steel PAFs compared to similar zinc-coated PAFs, further indicating that the zinc coating decreases pullout capacity. Hilti (2000) also presents data indicating that the surface condition of the base steel can affect pullout capacity. Under otherwise identical conditions, PAFs driven into steel with a rough unpainted surface (millscale and rust on surface) can show higher pullout capacities than PAFs driven into steel with a galvanized surface. It is suggested that the rough uncoated base steel surface may scrape some of the zinc off of the fastener, thereby increasing anchoring capacity.

A recent study (Hilti, 2000) also indicates that the presence of tensile stress in the base steel material can reduce pullout capacity. This factor is of interest, for example, when a PAF is driven into the tension flange of a beam. This study showed a reduction of pullout capacity on the order of 15 percent when the tensile stress level in the base steel was at about 60 percent of yield. The reduction in pullout capacity was about 40 percent when the tensile stress in the base steel was at the yield level of the base steel. This same study showed that the presence of compressive stress in the base steel had essentially no influence on pullout capacity.

An additional factor that may affect PAF pullout capacity is the specific tool used to install the fastener. Zobel (1968) indicates that the driving speed of the installation tool has an important effect on the fastener anchorage mechanism. This is further supported by Klee and Seeger (1986), which indicate that if all other variables remain constant, PAFs installed with different tools can lead to different pullout capacities.

Observations on Pullout Capacity

A review of both published and unpublished data sources, as discussed above, identified a number of factors that affect the pullout capacity of a PAF driven into steel. These include the embedment depth, base steel thickness and strength, fastener diameter, fastener surface finish (smooth vs. knurled), fastener zinc coating thickness, base steel surface characteristics, presence of tensile stress in the base steel, and the driving speed of the fastener installation tool. For a given fastener, the available data suggests that of all variables that affect pullout capacity, embedment depth is likely one of the most important. Interestingly, base steel thickness appears to have relatively little influence on pullout capacity, except for very thin base steels.

Currently, pullout values of PAFs for use in design are established in an empirical manner based on testing. Specific fasteners are tested for specific base steel and installation conditions. Design pullout values are then derived for use with field installation conditions that match the test conditions. Based on the numerous variables that can affect pullout capacity, this appears to be a reasonable and necessary approach. However, an understanding of factors that can affect pullout capacity is needed to extend the application of PAFs for field conditions that may differ from test conditions. An understanding of these factors is also necessary for proper testing of PAFs, to assure that all key variables are controlled and recorded in a test.

Data summarized in this paper provides some insight into the factors that may affect the pullout capacity of PAFs driven into steel. However, this data is insufficient to clearly quantify the combined effects of all variables on pullout capacity. The availability of additional test data that isolates and further quantifies the effects of individual variables would be a useful addition to the public domain research literature on PAFs. Further published data and studies on anchorage mechanisms for PAFs in steel would also contribute to an enhanced understanding of how various design variables may affect PAF pullout capacity.

CONCLUSIONS

Power actuated fasteners can be a useful alternative to more conventional fastening systems for making attachments to steel members. PAFs have been used in the construction industry for over fifty years. Yet, very little research and test data on this fastening system has been published in journals and other public domain research literature.

This paper has provided a brief overview of PAF fastening for steel, and has provided a state of the art review of factors affecting the pullout capacity of PAFs driven into steel. This review has been based largely on unpublished test reports. Further publication of PAF test data in the public domain by PAF manufacturers would be desirable to enhance the understanding and application of this fastening system by engineering research, design and construction professionals.

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