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Portable and Rapidly Deployable Bridges: Historical Perspective and Recent Technology Developments

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ABSTRACT

Portable and rapidly deployable bridges are critical for providing access routes for troops during military operations and for restoring vital lifelines for communities affected by large-scale disasters. This paper reviews the history and the state-of-the-art in portable and rapidly deployable bridge technology, primarily for U.S. systems. Four types of deployable systems are presented including (1) rapidly erectable gap crossing bridges (e.g. Bailey Bridge, Medium Girder Bridge), (2) vehicle launched bridges (e.g. Armored Vehicle Launched Bridge, Dry Support Bridge), (3) river crossing solutions (e.g. M4T6, Improved Ribbon Bridge), and (4) causeways (e.g. Navy Elevated Causeway System, Lightweight Modular Causeway System). Discussion of each design emphasizes the technology itself, its application throughout history, and the evolution of the forms in relation to one another. The paper concludes with a discussion of the future of these technologies. The paper provides the first review of portable and rapidly deployable bridge technology in civil engineering literature and is of general interest to those who would like to learn more about this technology for military and disaster relief purposes.

CE Database subject headings: Bridges; Military engineering; State-of-the-art reviews; History

INTRODUCTION AND MOTIVATION

Portable and rapidly deployable bridges are essential for the success of military operations and disaster relief efforts. These structures can provide access routes for troops in ship-to-shore and gap crossing operations. After natural disasters, they can restore vital lifelines to affected communities,

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including access to food, water, and medical supplies. With an expected increase in the number of natural and man-made disasters by a factor of five over the next fifty years, these technologies will become increasingly critical aspects of our civil engineering infrastructure (Thomas and Kopczak, 2005). Despite this fact, the study of post-disaster response has declined in the past few decades (McEntire, 1999). Little research or academic literature exists to address the logistical problem associated with disaster relief operations (Kovacs and Spens, 2007). Furthermore, the studies that do exist primarily focus on predicting and preparing for natural disasters, and not on the immediate response or reconstruction phase post-disaster strike (Kovacs and Spens, 2007).

Existing bridging solutions, typically comprised of aluminum or steel decks and capable of supporting loads up to Military Load Class (MLC) 70, were developed by the military during the mid-twentieth century (See Table 1 for a listing of military load classifications; the reader is directed to the original document for details of the hypothetical vehicles for each MLC (STANAG, 2002)). However, these solutions are approaching the end of their service life and there is an increasing demand for higher load carrying capability (Kosmatka, 2011). While all of these systems were designed for military purposes, many have also been used in emergency and disaster relief situations, a function which unfortunately may be increasingly required of them with the predicted rise of disasters (Thomas and Kopczak, 2005). As a point of reference, the reader is referred to three recent natural disasters which significantly impacted the transportation industry. As a result of the 2004 Indian Ocean Tsunami, hundreds of bridges along the western side of the Aceh peninsula in Indonesia were destroyed. Many of these bridges were critical links to communities, population centers, or industrial facilities (Cluff, 2004). The excessive bridge and road damage effectively disabled the transportation networks for hundreds of kilometers in this area and severely constrained the rescue and relief efforts (Saatcioglu et al., 2006). Relief efforts were similarly constrained after Hurricane Mitch struck Central America in 1998. In Honduras, the hurricane destroyed 98 bridge and 70,000 homes, and isolated entire communities (Howe and Robinson, 2001). 70-80% of the transportation infrastructure in the entire country was wiped out, including nearly every bridge. Thus, many of the rescue and relief efforts which ensued had to be performed with the use of helicopters (NOAA Satellite and Information Service, 2009). The hurricane left 70 percent of Nicaragua's roads unusable and wiped out 92 bridges (USGS, 2010). According to the National Climate Data Center, 192 of Costa Rica's bridges and 800 miles of its roads were affected by flash floods and mudslides as a result of the hurricane (NOAA Satellite and Information Service, 2009). As a result of Hurricane Katrina in 2005 in the United States, 44 bridges from the states of Louisiana, Mississippi, and Alabama, were impacted, incurring over one billion dollars in damage. Five of the 44 were completely destroyed, 20 were extensively damaged, 10 moderately damaged, and 9 were slightly damaged (Padgett et al., 2008). The three examples presented here give the reader a glimpse of the devastation that disasters can cause, as well as the potential for portable and rapidly deployable bridges in their wake.

Despite the demand for improvements and advancement in the technologies of rapidly deployable bridges, no easily accessible review of these bridges has been published in civil engineering literature. This paper will highlight advances in this technology over the last century with the aim of providing a state-of-the-art review of U.S. systems for a general audience who may be interested in learning more about this technology for military or disaster relief purposes. For further reading about military bridging systems outside of the U.S., the reader is referred to Jane's Military Vehicles and Logistics (Foss and Gander, 1991). This paper is divided into four main categories for portable and rapidly deployable bridges: (1) rapidly erectable gap crossing solutions, (2) vehicle launched solutions, (3) river crossing floating solutions, and (4) causeway solutions. Within these categories, forms will be discussed chronologically with a focus on the technology, the applications throughout history, and the evolution of design. Systems which are currently under development are also highlighted. Finally, the paper concludes with a discussion of the future of deployable bridge technology and current research.

RAPIDLY ERECTABLE GAP CROSSING SOLUTIONS

This section will present rapidly erectable gap crossing solutions, meaning bridges which are hand erectable on site and are elevated above a gap. This "Panel/Floor Beam/Deck" type of bridge was constructed as early as the first century B.C. (SDR Engineering Consultants, Inc., 2005). The most significant period of development for these rapidly erectable solutions occurred after World War I when military bridges employed during this conflict were deemed inadequate (Anon., 1935). This review begins with the development of the Callendar-Hamilton Bridges in 1930 and considers the evolution of this type through today. Many of these bridges have been vital to the success of the U.S. and Allied forces, as well as for disaster relief and post-conflict purposes.

Callender-Hamilton Bridges, 1930

The Callender-Hamilton bridge was one of the first modern military deployable bridges (Figure 1A) (Hamilton, 1935). This rapidly erectable bridge consists of modular, pre-fabricated truss panels with bolted connections (Anon., 1936). The key concept here was to employ standardized gusset plates to quickly build up a truss (SDR Engineering Consultants, Inc., 2005). It was devised by Gordon Douglas White-Parsons and Archibald Milne Hamilton in response to a call from the Royal Engineers of England to develop a lightweight military bridge after an investigation of the inadequacy of the constant cross-section military bridges employed during World War I. The call requested a bridge capable of spanning long distances while carrying military loadings, employing standardized parts with few connections, and being easily erectable under severe conditions (Anon., 1935).

Table 2 compares the Callender-Hamilton design to the constant cross-section military bridges that existed prior to 1930. The Callender-Hamilton provides a far greater amount of versatility and has a lower number of parts than other systems available at that time. The Mark II Truss, Inglis, Hopkins Light, and Hopkins Heavy all have a constant cross-section and therefore offer little versatility for longer spans or heavier loads. The Box Girder, a fifth system available at the time, provides the capability of varying the number of girders, thereby providing some opportunity for variable strength. The Callender-Hamilton, however, provides significantly greater versatility (Anon., 1935). It consists of Warren truss segments with chords and diagonals made of 10 ft (3.05 m) long angles. Additional strength can be gained by simply employing 2, 3, or 4 angles for each member. Trusses can be placed side-by-side to double the strength. Longer transverse members can be employed to permit additional lanes of traffic. Each module is 10 ft (3.05 m) in depth and

10 ft (3.05 m) long to permit easy transportation and calculation. This depth was sufficient to carry the current military loads of its day on spans up to 130 ft (39.6 m). To reach longer span lengths as shown in Figure 1A, the depth of the truss can also be doubled, requiring only the addition of a double-ended gusset plate to join Warren trusses (Anon., 1935).

Although developed primarily for military operations, this system could also be employed as civilian temporary bridges (particularly to replace bridges damaged during World War II) or as permanent bridges in regions in which it would be more difficult to erect a traditional bridge (e.g. mountainous regions, developing countries) (Anon., 1935; Hamilton, 1945). The Callender-Hamilton bridge was first put into service in 1935 as a temporary replacement for a masonry-arch vehicular and pedestrian bridge in Dulas, UK, which had been wiped out by severe flooding (Anon., 1936). After World War II, there were many extra Callender-Hamilton bridge components left in stockpiles. These were later shipped to France and the Netherlands and were constructed to replace destroyed bridges (Hamilton, 1947).

Bailey Bridge, 1941

The Callender-Hamilton system was improved upon by Sir Donald Bailey in 1941 with his design for a similar prefabricated portable bridge comprised of modular panels, known as the Bailey Bridge (Figure 1B) (SDR Engineering Consultants, Inc., 2005). A key improvement over the Callender-Hamilton system is in the connection: the Callender-Hamilton requires bolted connections to standardized gusset plates to build up a truss, while standardized Bailey Bridge panels can be connected by simple pins through pre-drilled holes (SDR Engineering Consultants, Inc., 2005; Thierry, 1946; Anon., 1944, 1936). This significantly increases the speed at which these bridges can be erected (Anon., 1944). Furthermore, the Bailey system is distinctive in its adaptability for a multitude of applications, including railway, pontoon, suspension, retractible and lift bridges as well as pier structures (Thierry, 1946).

As seen in Figure 1B, the Bailey Bridge is comprised of 10 ft (3.05 m) long, 5 ft deep (1.52m) prefabricated, high-tensile structural steel panels (Anon., 1954). Each panel weighs 600 pounds (272 kg) and can be carried by 6 people (Stewart, 1944; Thierry, 1946). Like its predecessor, panels can be constructed side-by-side or vertically in order to increase capacity or span length, as shown in Figure 1B (SDR Engineering Consultants, Inc., 2005). Up to four Bailey panels can be placed side-to-side and up to three stories tall (Department of the Army, 1986). This provides the system with the capability to carry military loads on spans up to 220 ft (67.1 m) (Thierry, 1946). In its pontoon form, which consists of the same panels being constructed and place on large floats, the Bailey Bridge has virtually no limit on span length (Anon., 1954). The Bailey bridge was originally designed only to accommodate one 10 ft 9 in (3.28 m) lane of traffic (Anon., 1954, 1945). Multiple lanes can be achieved by constructing separate bridges side-by-side or by using a flush deck with a common center truss between lanes (Anon., 1954; Thierry, 1946).

The elevated Bailey system offers the capability of two different erection processes: (1) launched from one side of a span to another and (2) lifted in place by a crane (SDR Engineering Consultants, Inc., 2005). When launched, the Bailey Bridge is generally built in one story first. The panels are joined together by pins and placed on top of rollers. As the panels are joined they are pushed out over the gap by means of a launching nose. The moment caused by the cantilevered end is counterbalanced by adding additional panels on the land side of the rollers (Anon., 1946). Once the structure is extended to the other side, the bridge is manually pushed forward until the end panels clear the rollers (Anon., 1944). After the first story is completed, additional panels can be added both vertically and horizontally to increase the load capacity (Anon., 1946). The time and personnel needed to construct the bridge depends on the type and length. The typical erection time ranges from 1 1/2 hours (for a 40 ft (12.2 m) single-single bridge, meaning one panel wide and one panel high) to 20 1/2 hours (for a 200 ft (61.0 m) triple-triple, meaning three panels wide and three panels high) (Department of the Army, 1986).

During World War II, a wide variety of prefabricated, portable bridges were developed. However, it was the Bailey Bridge that was one of the most widely used and became the standard design for the Allied forces (Thierry, 1946). The importance of the Bailey Bridge to World War II efforts is best exemplified by a quote from British Field Marshal Lord Bernard Law Montgomery: “Without the Bailey bridge, we should not have won the war” (Department of the Army, 1986).

While the design was used mainly for fixed and pontoon bridges, the system has been applied to many other structures, both for military application during World War II as well as for civilian use afterwards. Several Bailey suspension bridges were constructed, which remained the only standard vehicular suspension bridge during the war. They could be built to carry a 40 ton (36,300 kg) load over 200-400 ft (61.0-112 m) spans, but stretched to a length of 420 ft (128 m) (Thierry, 1946; Department of the Army, 1986). Bailey panels were used both for the decking and for the towers. Although construction for a Bailey suspension bridge was slower than that of a typical fixed bridge, it was sometimes necessary, especially when armies were traveling through mountain passes (Thierry, 1946). The system was also applied to railway bridges, which was used extensively in France. For this, the trusses were spaced closer together and often semi-permanent welded bracing was used (Department of the Army, 1986; Thierry, 1946). Lift and retractable bridges were also developed to allow the passage of vessels or to vary the length of the bridge during times of flooding (Thierry, 1946). Also, a Bailey bridge could be post-tensioned with additional cables to further strengthen the structure (Department of the Army, 1986).

After World War II, many extra Bailey bridge components were used for civilian application and several governments still hold stockpiles for emergency or training purposes (Anon., 1954). For example, they were used for falsework and scaffolding to build permanent bridges (Anon., 1958). The panels were used in a variety of structures and could create clear spans up to 150 ft (45.7 m). They were applied to runways, structural supporting steelwork, columns, and towers (Anon., 1954). Several were also used to temporarily replace collapsed bridges. One such example occurred in Ohio in 1969. A 79-year old steel truss bridge collapsed after being hit by a loaded tractor-trailer on September 21. Two Bailey bridges were delivered to site on November 6, and were constructed in eleven working days (Servaites, 1972). After bridges like these are dismantled, they are rejuvenated and prepared for use in another emergency event (Servaites, 1972).

The Bailey Bridge is still in use today by the U.S. military as well as by states' Departments of Transportation (DOT) for use in emergencies or during construction or rehabilitation of other bridges (SDR Engineering Consultants, Inc., 2005). After the 2004 Indian Ocean Tsunami, two

Bailey bridges were constructed in Indonesia to replace a steel truss bridge and a concrete precast box girder bridge which had been swept off their foundations. These Bailey bridges restored access to a cement plant, industrial facilities, and several communities which had been isolated by the event (Saatcioglu et al., 2006).

Bailey's 1946 patent expired in the 1970s providing the opportunity for further development of form by various firms including Acrow Ltd and Mabey and Johnson Ltd which will be discussed in later sections (SDR Engineering Consultants, Inc., 2005). Additionally, versions of the Bailey bridge such as the Janson Bridge and the Quadricon Bridge have been developed as more permanent bridging solutions (SDR Engineering Consultants, Inc., 2005).

Medium Girder Bridge (MGB), 1971

The Medium Girder Bridge (MGB), a lightweight, hand-erectable bridge which has been employed in military operations since 1971, offers improvements over the Bailey system in terms of weight and erection time (Figure 1C) (WFEL, 011a; U.S. Army Engineering School, 1994; Department of the Army, 1989). The MGB and Bailey systems are complementary: while the Bailey Bridge is primarily used for logistics, the MGB serves as a tactical bridge. When tactical bridging is no longer necessary, the MGB may be replaced by a Bailey system (U.S. Army Engineering School, 1994). Similar in concept to the Bailey system, the MGB consists of prefabricated deck panels and can be erected in single or double story configurations depending on demand (Department of the Army, 1989). A Link Reinforcement Set, comprised of reinforcing links that can be chained together underneath the girder, can be employed to provide additional depth, and therefore capacity, for the system (Department of the Army, 1989; WFEL, 011a). The difference between the single, double, and double with the Link Reinforcement Set configurations can be seen in Figure 1C. The deck panels are comprised of a specially fabricated combination of zinc, magnesium, and aluminum alloy, making them lighter in weight than the Bailey panels. All but three components are less than 440 lbs (200 kg) each, and can be carried and put into place by four people. The other three parts can be handled by six people (Department of the Army, 1989). Each bay is 6 ft (1.83 m) long and the decking system provides a 13 ft (4.00 m) wide roadway (WFEL, 011a;

Department of the Army, 1989). The system is designed to support MLC 60, but can be adapted to withstand MLC 70 with a reduction in the lifetime of the structure from 10,000 possible crossings to 7,000 crossings (U.S. Army Engineering School, 1994). With one bridge set, a 102 ft (31 m) bridge can be constructed. With two bridge sets and an additional reinforcement kit a 160 ft (49 m), MLC 60 bridge can be built (U.S. Army Engineering School, 1994; Department of the Army, 1989). A MLC 70 double story three-span bridge can extend to 249 ft (76 m). The system can also be employed as a floating bridge (WFEL, 011a).

A single-story MGB can be erected by 9 to 17 soldiers, a double-story can be erected by 25, and a reinforced configuration (shown in Figure 1C) can be erected by 34 (Department of the Army, 1989). The bridge is constructed on one side of the gap on top of a series of roller beams and is launched to the other side with the aid of a launching nose. One of the advantages of the MGB is that it can be constructed on unprepared and uneven ground. Alternatively, the MGB is air transportable and can be carried either in standard pallet loads or in a partially assembled configuration (Department of the Army, 1989).

Since its introduction, over 500 MGB systems have been purchased by different armed forces worldwide, especially by the United Kingdom, the United States and other North Atlantic Treaty Organization (NATO) allies. The MGB has also been employed for emergency relief operations, such as after the severe flooding in Venezuela in 2010 (WFEL, 011a). One MGB constructed for disaster relief can be seen in Figure 1C.

Acrow, 1973 & 1990

Acrow Ltd. improved on the design of the Bailey Bridge and actually produced two unique systems (Figure 1D). The first patent which involved a modification of the original Bailey panels came in 1973. Some of these improvements include trusses that use a higher grade steel, and thus are lighter and stronger than the Bailey panels. Additionally, the steel roadway deck panels more efficiently distribute the loads across the width of the bridge (Acrow Corporation of America, 2010, 2009). Finally, the Acrow 700XS series panels are 50% taller than the Bailey panels, standing 7’6” tall (2.29 m) (Acrow Corporation of America, 2009). The system was designed to carry the heaviest military tanks and earthmovers on the market. It can accommodate from one to three lanes and can span between 20 and 250 feet (6-76 m). Typically, the bridge is constructed on one side of the gap and cantilevered over the gap using a launching nose; alternatively, it can be erected with a crane (Acrow Corporation of America, 2009).

In 1990, Acrow submitted another patent which featured triangular panels rather than the traditional rectangular panels (SDR Engineering Consultants, Inc., 2005; Johnson, 1990). This new panel system addresses two main flaws in the existing Bailey design: (1) excessive sag (due to both elastic deflection and the required tolerance for pin connections) and (2) unnecessary steel at the neutral axis (when panels are added vertically such that the top chord of the lower panel is bolted to the bottom chord of the upper panel, a large amount of steel is concentrated at the neutral axis, thereby adding to the self-weight of the system but not to its bending capacity). Triangular panel configurations can reduce both the deflections and this concentration of steel at the neutral axis when stacked (the double chord at the neutral axis produced by stacked rectangular panels can be reduced to one neutral axis chord as the diagonal truss elements connect to just one center horizontal chord). Furthermore, Acrow adjusted the transverse cross-beam connections to reduce local bending stresses that occurred in the Bailey system and introduced temporary struts to reduce bending stresses that occur during launching (Johnson, 1990). As a result of these changes, this improved system increased the bending capacity by 50 percent and the shear capacity by 20 percent (SDR Engineering Consultants, Inc., 2005). This improved system can span between 20 and 300 ft (6 and 91 m) and is capable of carrying between 1 and 3 lanes of highway traffic (Johnson, 1990).

Like its predecessor, both of these Acrow systems are modular (in the same 10 ft (3.05 m) increments) and are capable of being stacked or connected side-by-side to increase capacity (Acrow Corporation of America, 2009; Johnson, 1990). The 700XS panels have been used by various military and United Nations (UN) groups (U.S., Australian, Canadian, and UN Peacekeeping Missions) both for logistical support bridges and for disaster relief missions. Additionally, they have been exported to over 50 countries for humanitarian assistance (Acrow Corporation of America, 2010). Recent applications include a temporary bridge commissioned by the New Jersey Turnpike Authority and a temporary system at Ground Zero to aid in recovery efforts following the events of September 11, 2001 (SDR Engineering Consultants, Inc., 2005). Acrow Corporation of America has these bridges available for both rent and purchase, which many different states and provinces have taken advantage of during bridge replacement and rehabilitation projects (Acrow Corporation of America, 2010).

Mabey Logistic Support Bridge (Mabey-Johnson Bridge), 1987

Like Acrow Ltd, Mabey & Johnson Ltd improved upon the Bailey Bridge through patents in 1987 and 2003 (Figure 1E) (SDR Engineering Consultants, Inc., 2005; Mabey and Mabey, 1987; Forsyth et al., 2003). This system relied on the same, rectangular lattice panels in the original Bailey design, but proposed panels of varying depths so that the final girder configuration would more closely resemble the bending moment diagram. The addition of these transitionary panels (middle panel in the Mabey-Johnson section of Figure 1E) would reduce the self-weight of the system and increase its efficiency (Mabey and Mabey, 1987). Another way that greater efficiency was achieved was by increasing the camber of the structure. This was accomplished by bolting the bottom chord while including spacers between modules of the top chord (SDR Engineering Consultants, Inc., 2005). The 2003 patent further improves on the Bailey system by proposing a modular system for panel construction on-site (including varying length chord members and modular webs). This system would aim to provide greater versatility in panel strength, eliminate expensive joints between prefabricated panels, and reduce packaged size for transportation while not significantly increasing erection time (Forsyth et al., 2003). Manufacturing of this modular panel system can be expedited by using robots over traditional manual welding (Anon., 1990).

The Mabey Johnson system has been constructed worldwide both as permanent and temporary structures. However, because of the ease of erection and transportation, it has been widely used as a temporary bridging solution (Goodridge, 1998). For example, in 1998 a 197 ft (60 m) Mabey-Johnson bridge was constructed in just one weekend as a temporary structure during construction on an existing bridge in London. Mabey & Johnson Ltd keeps several bridges in stock for use in emergency situations such as natural disasters and post-conflict solutions (Goodridge, 1998). Thirteen Mabey-Johnson bridges were constructed in Costa Rica after Hurricane Cesar in1996, and in 1998 the U.S. military constructed several more in Bosnia after the conflict (Goodridge, 1998). After a flash flood washed away a highway bridge in New Mexico, a replacement bridge from a New Mexican DOT stockpile was delivered to site within 24 hours and constructed within one week (SDR Engineering Consultants, Inc., 2005). Additionally, it was the primary logistical purpose bridge that was constructed during Operation Iraqi Freedom in 2003 (Sykes, 2005). When in the field, the bridge can be constructed using only hand tools (Goodridge, 1998). The 882 lb (400 kg) bays are joined together with bolts, and can be put into place by hand or by means of a crane (Goodridge, 1998). This system also has the capability of being used as a floating bridge (Milligan, 2004).

VEHICLE LAUNCHED SOLUTIONS

Vehicle launched bridges, including any form which is launched directly from a tank or truck, are erected with the aid of a mechanical system instead of simply being assembled by hand and pushed out over the gap. The need from such systems stemmed from tank warfare starting in World War I when tanks needed to cross gaps en route to or on the battlefield. Early versions of this form can be traced back to British designs during World War II. Known as scissor-bridges, these forms were mounted on Covenanter and Valentine type tanks and were capable of spanning 30 ft (9.1 m) and supporting 30 tons (27,200 kg). A one-piece variation mounted on Churchill tanks was also developed for the same span length but with double the load carrying capacity (Anon., 1942). These forms have been further developed and employed through today. This section will emphasize systems developed from World War II to present day.

Armored Vehicle Launched Bridges (AVLB), c.1942

Armored Vehicle Launched Bridges (AVLB) are launched from a tank, unfolded, cantilevered to reach the other side, and released to act as a simply supported span during use (Figure 2A). Afterward, the bridge is retrieved by the tank on the opposite side (U.S. Army Engineering School, 1994). The U.S. military used the AVLB in conjunction with standard M60 or M48 tanks. These systems could support MLC 60 loads over a 60 ft span (18.1 m) (U.S. Army Engineering School, 1994). In an effort to move toward a uniform heavy chassis for all of its tanks, the U.S. military is now replacing these bridges with the Titan AVLB. This revised system can support spans as long as 85.3 ft (26 m) with higher loads and is compatible with M1A1 tanks (Foss, 2005; Bank et al., 2006). This revision also provides full protection for the soldiers operating the bridge deployment as well as greater mobility compared to its predecessor (Foss, 2005). The AVLB is an ideal bridging solution for spanning smaller dry or wet gaps, particularly for streambeds, antitank ditches, craters, canals, partially destroyed bridges, or other similar obstacles (Department of the Army, 1985).

Dry Support Bridge (DSB), 2003

The Dry Support Bridge (DSB) is actually a descendant of the MGB, but is included in this category since the system includes a vehicle launcher (Figure 2B). The DSB, like its predecessor, is a modular, pre-fabricated bridge. The DSB has two main advantages over the MGB: (1) ease and speed of erection and (2) a significantly reduced number of components. It can span up to 130 ft (40 m) with a 14 ft (4.3 m) roadway and can support MLC 80 (DiMarco, 2004). Panels are entirely comprised of an aluminum alloy and can be shipped in typical ISO (International Organization for Standardization) containers, standard flat bed trucks, by helicopter, or by rail (DiMarco, 2004; WFEL, 011b).

Using the vehicle launcher system, erection of a 130 ft (40 m) span can be completed with just eight soldiers in 90 minutes. The bridge is deployed from a hydraulically operated launching vehicle from one side of the gap (DiMarco, 2004). In order to accomplish this, a beam is first cantilevered out over the gap by the launching vehicle until it reaches the opposite bank. The modules of the bridge are then unfolded and pushed out underneath this beam with the help of a crane (WFEL, 011b; DiMarco, 2004). After the bridge is completed the launching beam is recovered and restowed in the launcher vehicle (WFEL, 011b).

The DSB has been used in the field in the United States, Germany, South Korea, and Iraq (WFEL, 011b). It has been used for over 18,000 simulated crossings without a single failure. According to Lieutenant Colonel Tom Svisco, project manager of the U.S. Army bridging group, "The M-18 Dry Support Bridge is revolutionary compared to the way we've been doing bridging of this type up to now, with fewer soldiers required, less time to assemble and disassemble, a greater MLC rating and better transportability" (WFEL, 011b). It is predicted that 100 DSB systems will be employed over the next 10 years (WFEL, 011b).

Composite Army Bridge (CAB), Under Development

Due to the limited load carrying capacity, the difficulty in retrofitting, and the high self-weight of existing vehicle launched solutions, the Army has begun investigating a vehicle launched solution which is completely comprised of composite material, specifically employing SCRIMP infused carbon/epoxy for the bridge decking (Kosmatka and Policelli, 1999; Kosmatka, 2011). Two Composite Army Bridge (CAB) can be carried by the existing General Dynamics M1-A1 launching vehicle, allowing for greater mobility before the launcher is required to retrieve or reload the bridges (Figure 2C). By employing composite material, this solution offers a 20% reduction in cost and a 25% reduction in self-weight compared to an aluminum vehicle launched solution (Kosmatka and Policelli, 1999; Kosmatka, 2011).

FLOATING SOLUTIONS

There are many different variations of pontoon bridges from military to civilian, temporary to permanent structures. The term "pontoon bridge" is used to refer to any bridge which floats on top of the water by means of some watertight float or vessel. The majority of these bridges have been deployed for temporary military purposes, but have also been constructed in emergencies (Beretta, 1941). Additionally, several of the rapidly erectable gap crossing forms that have already been discussed (e.g. Bailey, Medium Girder Bridge) have the capacity to be constructed as floating bridges or ferries.

Floating bridges have been used from ancient times since the army of Darius I in 513 B.C. or before, and are still standard equipment for all modern armies (Beretta, 1941; Herodotus, 1914). History is strewn with examples of how these pontoon bridges were particularly advantageous in battle. As of 1941, the standard military pontoon bridge consisted of floats (or pontoons) which are connected with a deck (Beretta, 1941). Each pontoon is anchored to the river bed with a cable. The load is distributed to several pontoons with the continuous beam action of the decking; thus, the load capacity is determined by the entire system instead of any one particular pontoon. This system can be deployed in a matter of hours (Beretta, 1941). One example of an emergency structure of this type is the bridge replacement between Hidalgo, Texas, and Mexico. In 1939 the permanent structure collapsed, so an emergency floating bridge was constructed, and the pontoons made of wooden boats. It took two weeks to construct the bridge and it was in service for one year (Beretta, 1941). Modern floating bridges are discussed in the following sections.

M4

An early design for a military pontoon bridge, the M4, is a modular bridge comprised of a hollow aluminum decking system and aluminum pontoons (Figure 3A) (Department of the Army, 1970, 1954). The 13.9 ft (4.23 m) wide deck acts as both stringers and floor and is comprised of individual deck balk. The deck balk is staggered and pinned at three points to create continuous beams (Department of the Army, 1970, 1954). Supporting floats, that lie perpendicular to the deck, are comprised of two half pontoons that are joined together stern-to-stern and are spaced 15 ft (4.57 m) center-to-center to support the superstructure. Each half pontoon is nearly 7 ft (2.13 m) wide by 30 ft (9.14 m) long by 3.5 ft (1.07 m) deep and weighs 1,750 pounds (794 kg). The pontoons are tapered so that they can be nested together during transport. The decking system attaches to these pontoons by means of a gunwale which fasten to each side of the pontoons (Department of the Army, 1970). For the typical pontoon spacing at 15 ft (4.58 m), the structure can support MLC 60 load in stream velocities up to 5 ft/s (1.52 m/s). The system can be reinforced by decreasing the spacing between pontoons. For example, by spacing the pontoons at 7.5 ft (2.29 m) increments, the bridge can carry MLC 80 load in stream currents of 8 feet per second (2.44 meters per second). Alternatively, a combination of whole and half-pontoons can be used. Finally, pneumatic floats can be placed in between the aluminum pontoons. In this scenario the superstructure is pinned only to the pontoons and the floats solely provide vertical support for the superstructure. However, this method is a less desirable reinforcement scenario as it creates an unstable structure and is difficult to adapt into other reinforcing schemes. (Department of the Army, 1970). The M4 can be constructed as a floating bridge, fixed bridge (single spans up to 45 ft (13.7m), as further discussed in the M4T6 section) or ferry (Department of the Army, 1954).

Class 60

Class 60 floating bridges are comprised of a steel-grid deck supported by pneumatic floats which are placed 15 ft (4.57 m) center-to-center (Department of the Army, 1988a) (Figure 3B). The pneumatic floats are comprised of two half-floats that are 9 ft (2.74 m) wide by 3 ft (0.91 m) high by 22 ft (6.71 m) long. Each half float consists of three adjacent tubes which are tapered upwards at the ends and are oriented perpendicular to the longitudinal axis of the bridge (Department of the Army, 1988c). Saddle assemblies consisting of eight interior saddle panels, two outrigger panels, and two saddle beams which rest on top of the floats complete the substructure (Department of the Army, 1988c). The deck is comprised of tread panels (wide flange sections that are welded to supporting stringers) supported by the saddle beams and filler panels which rest between these tread panels. Panels are connected to one another by pins. Curbs are placed on either edge of the bridge and ramps are added to either end to provide an inclined support (Department of the Army, 1988a). A typical Class 60 bridge can be up to 135 ft (41.1 m) long (Department of the Army, 1970). The system can support MLC 70 loading with currents up to 8 ft/s (2.44 m/s) (Department of the Army, 1993). Construction requires one, but preferably two, cranes as well as an air compressor and two bridge erection boats. It takes approximately an hour to construct the first 90 ft (27.4 m) of the bridge, with a subsequent rate of deployment of 120 ft/hr (36.6 m/hr) (Department of the Army, 1970).

M4T6, c. 1940s

The M4T6 floating bridge, developed after World War II, is a combination of the best aspects of the M4 and Class 60 bridges discussed in the two previous sections (Figure 3C) (Department of the Army, 1988c). More specifically, it employs the superstructure of the M4 and the substructure of the Class 60 (Department of the Army, 1970). Note that in Figure 3C, schematics for the M4 and Class 60 bridges were taken from manuals on the M4T6, since schematics for these other bridges were not available and the M4T6 is based on these two solutions. The M4T6 system can support a MLC 70 with currents up to 8 ft/s (2.4 m/s) (Department of the Army, 1993). Both the M4 and Class 60 forms require more time and personnel to construct than the M4T6. As a result, both became obsolete with the introduction of the M4T6. Until 1972 when the Ribbon System was introduced, the M4T6 was the floating bridge of choice for military operations (Department of the Army, 1988c)

Several different configurations of the M4T6 are possible and range from four to six floats, with either a normal or reinforced deck. The normal bridge has a span of 141 ft (43 m). The bridge is hand erectable and can be either air transported or carried by 12 standard military cargo trucks, which also carry the tools and rigging equipment necessary to construct the bridge. In daylight conditions this bridge will take somewhere between 2.25 and 3.75 platoon hours to construct, depending on the particular configuration chosen. For example, two companies could construct a 300 ft (91.5 m) bridge in 4 hours (Department of the Army, 1987). It will take 50% longer to construct at night, and 50% longer to construct a reinforced version of the bridge (Department of the Army, 1988c, 1987). To erect the system, pairs of floats are connected together on one shore of the waterway, and the appropriate saddle components and balk are attached. As the construction progresses, the raft is pushed across the gap until it has reached the opposite shore (U.S. Army Training Support Center, 1988).

In addition to being utilized for floating structures, the superstructures of some floating bridges (the M4, the M4T6, and the Class 60 bridges) can be erected as fixed, elevated bridges (Department of the Army, 1970). This method is used primarily to cross narrow streams or dry gaps (Department of the Army, 1970). If a longer span is desired, additional trestles or piers may be used as intermediate supports (Department of the Army, 1970).

Improved Float Bridge (IFB, Ribbon), 1972

The Improved Float Bridge (IFB or Ribbon) is a modular, floating bridge comprised of an aluminum superstructure and floating supports developed at the United States Army Mobility Equipment Research and Development Command (Figure 3D) (Department of the Army, 1988b). The design was based on photographs, drawings, and segments of the Soviet Union's PMP (Pomtommo

Mostovoj Park, or pontoon bridge set) Floating Bridge (Department of the Army, 1988b; Anon., 2011). The PMP, based on a pre-1945 German design and considered to be a significant advance in floating bridge technology, featured a similar design but employed a steel superstructure (Anon., 2011). The American, aluminum design resulted in reduction of self-weight by a factor of 1.2 for river pontoons (5440kg compared to 6676kg) and by a factor of 1.4 in shore pontoons (5310kg compared to 7252kg) (Anon., 2011). The PMP is still in use in the Czech Republic and Slovakia (Anon., 2011).

Ribbon Bridges are transported in folded sections by modified U.S. Army M812 or M945 trucks (Department of the Army, 1993). Schematics of the deployment operation can be seen in Figure 3D. Similarly, the PMP bridge is carried on a truck in the folded position. When ready to deploy the travel locks are disengaged and the truck backs up towards the water. When it suddenly stops the module slides into the water and unfolds. Six locking devices are activated to stiffen the pontoon, and the module is brought into position with the aid of boats (Anon., 2011). Modular sections of the Ribbon Bridge include ramp bays for each bank and interior bays (Department of the Army, 1993). This design provides a 13ft 5in (4.089m) wide roadway with two 4ft (1.219m) walkways on either side (Department of the Army, 1993). It is capable of supporting MLC 70 with currents as fast as 8 ft/s (2.4 m/s) (Department of the Army, 1993).

As of 1988, the Ribbon Bridge was the primary floating bridge used for assault by the U.S. Army (Department of the Army, 1988b). However, due to the advent of the Improved Ribbon Bridge in 2003, this system has now become obsolete (DiMarco, 2004).

Improved Ribbon Bridge (IRB), 2003

In 2003, the Improved Ribbon Bridge (IRB) was developed as a direct replacement to the Ribbon Bridge (Figure 3D). The new system can withstand 80 ton (72,500 kg) loading for a tracked vehicle and 110 ton (99,800 kg) loading for a wheeled vehicle, with currents up to 10 ft/s (3.05 m/s). This increase in load capacity was accomplished by means of an aluminum strong-back forging in both the ramp and interior bay modules. The deck width was also increased to 14.8 ft (4.5 m) to permit two way traffic for small vehicles. The bridge is air transportable and can be configured as a fixed, floating bridge or as a ferry (DiMarco, 2004; Puryear, 2010). The IRB system was given to bridging companies in Southwest Asia and was successfully used in Iraq (DiMarco, 2004).

CAUSEWAY (SHIP-TO-SHORE) SOLUTIONS

Causeway systems, meaning deployable solutions which connect ships to shore, primarily facilitate the transportation of supplies and equipment. One of the first deployable causeway systems to be designed was the Mulberry Harbour during World War II. Allied commanders realized that they needed a portable harbor to be able to re-supply troops inland (Potts, 2009). This system, designed as a temporary harbor, consisted of 213 concrete caissons which formed the inner breakwater, 23 pierheads to connect 10 miles (16 km) of steel roadway, and floated on 500 steel and concrete pontoons that were enclosed in 93 different steel outer breakwaters. Unfortunately, after only several days' use one of the two systems constructed was destroyed by a large storm after not being properly anchored to the seabed. Nevertheless, the other was in operation for five months following its construction in Normandy just after D-Day. Despite the fact that General Eisenhower stated that the "Mulberry exceeded our best hopes" and helped the Allied Forces win the war, it was not constructed again (Potts, 2009). Later causeway systems would not try to replicate the artificial harbor idea and would focus on the transportation of supplies from ships to land. Once again, all of the systems presented are U.S. military systems, but several have also been noted for their potential after natural disasters. These systems could be particularly beneficial if the port infrastructure was destroyed or to reach areas that are too shallow for ships to navigate.

Early Causeway Systems: Navy Lighterage System (NLS, c. 1960s) and Modular Causeway System (MCS, 1984)

The Navy Lighterage System (NLS) and the Modular Causeway System (MCS) were primarily employed to offload cargo and vehicles from ship to shore by the Army and Navy, respectively. Both are modular systems that are capable of operating in Sea State 2 (SS2) conditions (see Table 3 for a review of Sea State conditions) (Garala, 2004; Fort Eustis Weather, 2012).

The NLS is a steel modular system, comprised of 21 ft (6.40 m) wide by 90 ft (27.4 m) long sections that have been used for the last 40 years (Garala, 2004; Anon., 2012). Due to the large size of these panels, special lifting equipment was required to utilize the NLS. Furthermore, these sections exceeded the dimensions of ISO freight containers. Increased interest in transportation by ISO freight containers during the 1980s led the Army and Navy to consider developing a causeway system capable of fitting within standard ISO dimensions. As a result, the MCS systems was developed (Anon., 2012).

The MCS is comprised of floating steel modules which can be configured into four different systems. These include the Floating Causeway (FC, Figure 4A), the Roll-On/Roll-Off (RO/RO) discharge facility, the Causeway Ferry (CF), and the Warping Tug (WT). The first two of these are non-powered platforms, the CF is comprised of both powered and non-powered sections, and the last is made of solely powered modules (Buonopane, 2002). Each of the subsystems are made up of a group of interoperable and interchangeable modules which can be connected both side-to-side as well as end-to end (Department of Defense Office of the Inspector General, 2004). The MCS can be transported in standard ISO containers and has the capacity to support both tracked and wheeled vehicles, including main battle tanks (Buonopane, 2002). The system is operable through SS2 conditions and the anchor system can survive through a SS4 (or SS5 if drag anchors are used) (Buonopane, 2002).

The Army adopted the MCS system, while the Navy decided to instead focus on developing a modular Navy Elevated Causeway System (see discussion of this system in the following section) (Anon., 2012).

Navy Elevated Causeway System (ELCAS, 1975) and Navy Modular Elevated Causeway System (ELCAS (M), c. 1985)

The Navy Elevated Causeway System (ELCAS), developed jointly by the Army, Navy, and Marine Corps, is a deployable pier facility employed for moving cargo and equipment to shore during amphibious operations (Figure 4B) (Groff, 1992). The ELCAS is comprised of NL pontoons which are elevated 20 ft (6.10 m) above mean low water level and supported by piers (Groff, 1992). Other than the piles which must be driven a certain distance below the mud line of the ocean floor, the ELCAS is a completely prefabricated, modular structure. The components of this system include a ramp, roadway surface, pier head, turntable, fender, and pile foundation. The construction begins from the beach and the causeway is built out towards the ship (Lin, 1999). Modular sections are first connected on the beach. The piles are driven and the sections are temporarily set floating beneath them. The sections are then lifted one by one. In order to accomplish this, the module is disconnected from the other floating sections, elevated with the lifting jacks, and connected to the previously elevated members. These connections are reinforced with permanent welded gusset connections and additional side connectors (Skaalen and Rausch, 1977). Once construction of the the causeway is completed, a crane can be used to move containers from the offshore ship or barge onto flatbed tractor-trailer trucks that then drive along the causeway to deliver supplies. The trucks are able to turn around on the turntable located at the offshore end of the causeway. The 21 ft (6.40 m) width of the causeway allows trucks to pass each other and to travel back and forth efficiently (Groff, 1992). The system was advertised as being operable in SS3 conditions. Unfortunately, in practice it is only operable through SS2 (Deitchman, 1993).

The ELCAS remains one of the only practical methods for transferring equipment and supplies over the surf-line. Design for the system started in 1975 and was meant to replace the NL causeway system Groff (1992). It was critical that a system capable of transferring supplies over the surf-line be developed, since it was expected that by 1985, 85% of all U.S. container-capable ships would require developed beaches and ports in order to unload their contents (Skaalen and Rausch, 1977). With the advantages over previous systems, the ELCAS has particular benefits for both military and nonmilitary applications. The ELCAS may be used to deliver large quantities of humanitarian relief or construction equipment after natural disasters such as floods, earthquakes, typhoons, or hurricanes. In order to facilitate rapid construction, a modular version, named the Navy Modular Elevated Causeway System (ELCAS (M)), was later developed (Groff, 1992).

Joint Modular Lighter System (JMLS), 1991

The NLS and MCS are only capable of operation in up to SS2 conditions. Due to an increased interest in operation under SS3 conditions, a joint Army and Navy program was launched in 1991 to develop the Joint Modular Lighter System (JMLS) as a replacement for both the NLS and MCS which could operate under SS3. The JMLS consists of 40 ft (12.192 m) long, by 8 ft (2.438 m) wide, by 8 ft (2.438 m) high modules which can be connected both side-to-side or end-to-end. The modules can be connected three abreast in order to create super-assemblies that are 24 ft (7.315 m) wide. The modules are rigidly connected by means of interlocking male and female components on the ends, or by means of side connectors to extend the width of the platform. This system can be applied to either powered or non-powered configurations (Garala, 2004).

During testing of the JMLS, several shortcomings were found. Despite the fact that it was designed to be operational under SS3 conditions, it can neither be assembled nor safely operated under these conditions. With SS2 conditions or above, stress between the modules cause the welds to develop cracks. Finally, the system is intensive to maintain and the many obstructions on the deck makes the system hazardous to personnel. To overcome these deficits, the Improved Navy Lighterage System (INLS) was designed (Garala, 2004).

Improved Navy Lighterage System (INLS), c. 1990s

Due to the failure of the JMLS to remain operational in SS3 conditions, the Improved Navy Lighterage System (INLS) was developed using a variation of the 40 ft (12.192 m) long, by 8 ft (2.438 m) wide, by 8 ft (2.438 m) high modules of the JMLS but employing composite material (Figure 4C) (Garala, 2004). By using composite material instead of steel, the INLS weighs 25% less than the NLS, lifetime system cost is reduced, and corrosion of structural components is minimized. Like the JMLS, the system is comprised of several powered and non-powered modular components, which are assembled as different floating platforms, and are interchangeable. The four different types of platform include the Warping Tug (WT), the Causeway Ferry (CF), the Floating Causeway (FC), and the Roll-on/Roll-off Discharge Facility (RRDF). The system was designed to be fully operational in SS3, to sustain only minimal damage under SS4, and to structurally survive a SS5 event (Garala, 2004).

Lightweight Modular Causeway System (LMCS), Under Development

Several shortcomings exist in the current modular causeway systems. For example, none of the current systems can be deployed in certain environments like mudflats or wetlands. Additionally systems like the MCS, INLS, and IRB are excessively heavy, require intensive in-water assembly with substantial support equipment, occupy a significant storing volume, and with the exception of the IRB are not air liftable (Fowler et al., 2006). Futhermore, the Department of Defense is forecasting an increasing need to be able to offload vessels in more austere environments and in shallower water than these systems allow (Deming, 2009). Thus, in order to overcome the shortcomings of these other systems, the Lightweight Modular Causeway System (LMCS) is under development (Figure 4D). The current prototype of the system shows a 50% reduction in self-weight and a 50% reduction in packaged volume from current systems (Fowler et al., 2006). Deployment under more austere conditions or in shallower water is accomplished by only partially inflating the end floats, which effectively creates a ramp (Deming, 2009). Having some of the floats only partially filled would also be beneficial over rivers with variable widths or for causeways as the tide changes.

The current LMCS prototype consists of 10 ft (3.05 m) by 20 ft (6.10 m) modules which are comprised of both an aluminum decking system and supporting pneumatic floats (Ferguson, 2010). Pneumatic floats are deflated during packaging and simply inflated during use. Inflation can be completed rapidly since the floats are not filled with high pressure air and require no external pumps to inflate. They can either be filled using pre-pressurized compressed air or lightweight portable blowers. The float closest to the shore can be partially filled to provide a ramp. High strength, but lightweight fabric is used for the floats to avoid puncture and abrasion. Hinges comprised of high-strength elastomeric springs are used to join the modules together (Deming, 2009). While these do not provide full moment resistance, the load from a vehicle traveling over the causeway is distributed over and supported by several modules (Ferguson, 2010). A 120 ft (36.6m) causeway can be shipped in the footprint of three ISO containers, and the system can be transported to site by land, sea, or air (Deming, 2009). Additionally, it can be transported by the Joint High Speed Vessel (JHSV) whereas other causeway systems cannot (Fowler et al., 2006). This will allow the LMCS to access significantly shallower ports than previously possible. A 120 ft (36.6 m) causeway can be deployed in 3 hours by only 7 people, and can be retrieved in a similar amount of time (Deming, 2009). The causeway capacity is sufficient to support two 74 ton (67000 kg) M1A2 main battle tanks (or two M1A1 Abrams tanks) (Fowler et al., 2006).

While the design for the LMCS has not been finalized, a full-scale prototype has been fabricated and tested on multiple occasions. A 70 ft (21.3 m) section was deployed over a rapidly flowing river to simulate a post earthquake response. The entire procedure was accomplished by 20 soldiers. After the bridge was deployed, mooring lines were used to secure the bridge to anchor points on land. Another simulation was performed to demonstrate the deployment of the system at an austere landing site, and a third was done by delivering the system via helicopter (Ferguson, 2010).

MOSES, Under Development

Unlike the other causeway systems discussed thus far, the MOSES system, originally design for the Navy by the Center of Innovations in Ship Design project team, is entirely inflatable and rests on the sea floor as opposed to floating at the surface (Figure 4E). It is essentially a large fabric bag that is filled with water and rests on the sea floor to provide stability. The top surfaces is flat and can be lined with planks to serve as a roadway. Air-beam supported walls frame the roadway, thereby protecting it from ocean waves. The system can be stored in a rolled configuration. Deployment occurs by first pumping air into the bag and walls, and then pumping seawater into the bags. This system is only in the testing phase and suggestions have been made to further improve the stability and rigidity of the walls to better withstand wave impact. The system is projected to be able to withstand SS4 conditions (Mallen and Testerman, 2008).

CONCLUSIONS

This paper has highlighted the most important innovations in deployable and portable bridge technology by the U.S. military. This review has mapped the evolution of rapidly erectable gap crossing, vehicle launched, floating, and causeway solutions. By presenting not only the technology itself, but also its applications throughout history and the evolution of the forms in relation to one another, this paper aims to provide a review for a general audience interested in temporary bridge technology for military and disaster relief applications.

In addition to providing a review of older deployable and portable bridge technology, this paper also highlights recent advancements and designs currently under development, including the Dry Support Bridge, the Composite Army Bridge, the Improved Ribbon Bridge, the Lightweight Modular Causeway System, and MOSES. Each of these newer systems has been aimed at reducing erection times, decreasing self-weights, and improving load carrying capability to meet the increasing demands of the U.S. military. The DSB improves upon the legacy of pre-fabricated modular bridge systems, like the Callendar-Hamilton, but requires less components and employs a vehicle launcher for faster erection. By using advanced composites, the CAB decreases the self-weight and increases the load-carrying capacity of vehicle launched bridges. The IRB increases load carrying capacity of floating bridges by improving the strength of the ramp and interior modules of the Ribbon Bridge. The LMCS shows great potential by being capable of operation under much more austere environments and in shallower water. The current prototype suggests improvements in self-weight and packaged volume by a factor of two in comparison to prior systems. Finally, MOSES suggests an entirely new conceptual design for causeways.

These new systems show that great strides are being made to meet the increasing demand from both military and disaster relief perspectives. Nevertheless, there are still significant opportunities for improvement on these systems for designers of temporary bridge technology today. With advancements in new composite materials such as fiberglass, significantly lighter bridges may be possible. The groundwork for such systems has already been broken by the Improved Navy Lighterage System and the Composite Army Bridge, and further research on fiberglass reinforced polymer (FRP) bridges is described in recent articles (e.g. (Hanus et al., 2006); (Wight et al., 2006)), but new systems could improve further upon this work. The current causeway systems still fall short of their operational goals of remaining functional through higher Sea States. Finally, with the predicted increase in large scale disasters, perhaps designers will start to consider designing bridges specifically to meet this need. With the unique challenges of a disaster relief environment, certain demands such as load capacity, available tools for erection, personnel involved, etc. could be drastically different from those governed my military operations. As a result, the optimal bridge to be designed for disaster relief efforts could be quite different than the systems which are currently available.

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MLC	$Tracked\ (ton(kg))$	$Wheeled\ (ton(kg))$
60	60 (54,400)	70 (63,500)
70	70 (63,500)	80.49 (73,000)
80	80.01 (72,600)	72.58 (65,800)

TABLE 1. Military Load Classification (Data reprinted from STANAG 2002, courtesy of U.S. Army/Navy/Air Force). *The first column provides the designation, the second and third lists the associated load for tracked and wheeled vehicles, respectively. Only load cases discussed in this paper are included.*

$Name$	$Span,\, ft(m)$	$Description$	$No.$	$Wt.\, tons(kg)$
Mark II Truss	40-70 (12-21)	Warren girder on panels	15	1.47 (1330)
Inglis	60-108 (18-33)	Warren truss with tubular members	6	0.45 (408)
Box Girder	32-96 (10-29)	Deck bridge on 4 box girders	2	0.65 (590)
Hopkins Light	75-105 (23-32)	Warren truss with channel members	22	0.52 (472)
Hopkins Heavy	105-150 (32-46)	Warren truss with channel members	22	0.52 (472)
Callender-Hamilton	30-200 (9-61)	Warren truss with angle members	11	0.21 (191)

TABLE 2. Comparison of Military Bridge Technology after World War I (Table reprinted from Anon. 1935, with permission from Engineering). *The first column provides the name, the second the range of spans, the third describes the system, the fourth lists the number of major parts and the fifth lists the weight of the heaviest part.*

SS	$Wave\ (ft(m))$	$Wind\ Speed\ (Kts(km/hr))$
2	1.5-3.5 (.45-1.07)	9-14 (16.7-25.9)
3	3.5-6 (1.07-1.83)	14-18 (25.9-33.3)
4	6-8 (1.83-2.44)	18-21 (33.3-38.9)
5	14-25 (4.27-7.62)	21-27 (38.9-50.0)

TABLE 3. Pierson - Moskowitz Sea Spectrum (Table reprinted from Fort Eustis Weather (2012) *The first column provides the Sea State number, the second and third columns list the associated wave and wind speed ranges. Only Sea States discussed in this paper are included.*

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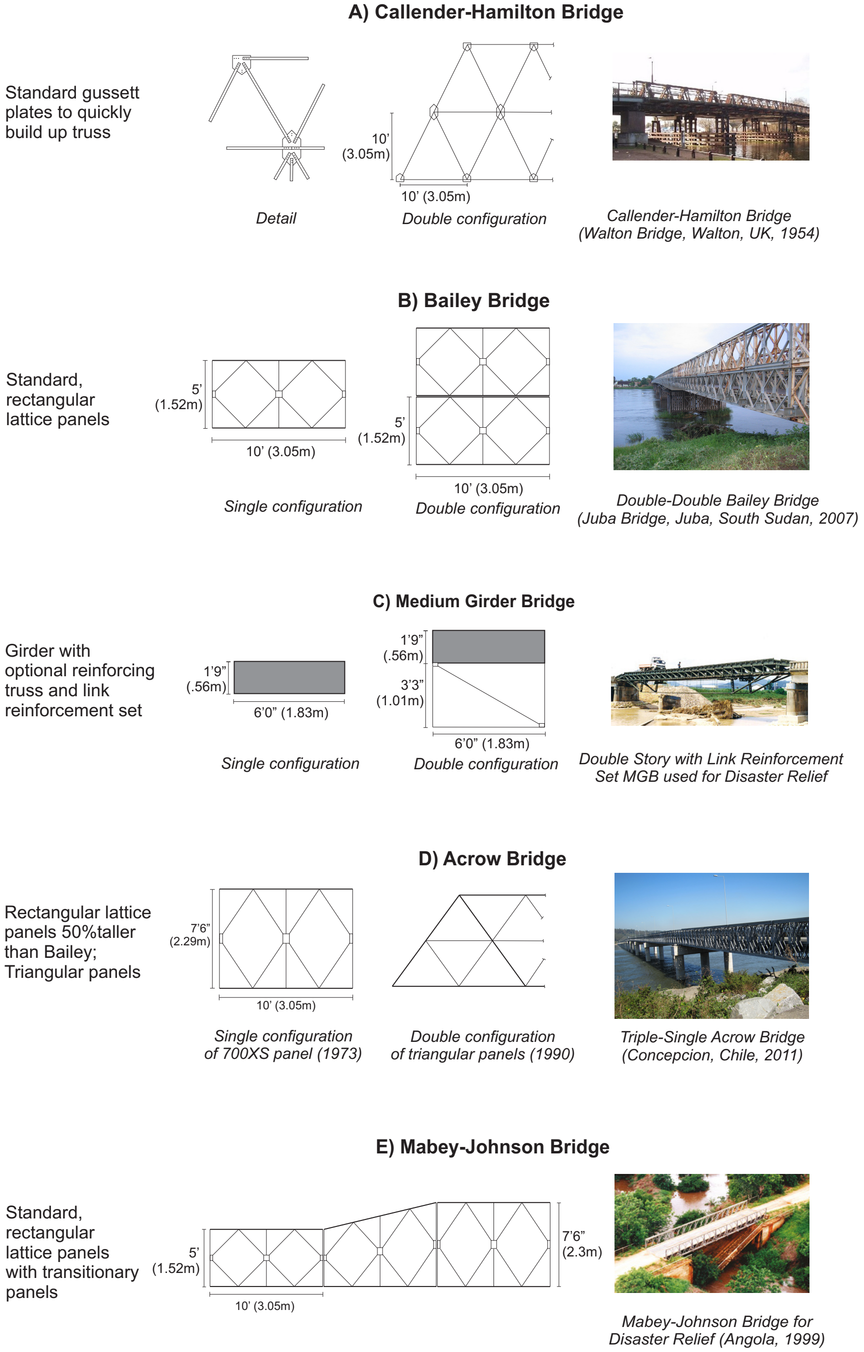


Detail

Double configuration

Callender-Hamilton Bridge (Walton Bridge, Walton, UK, 1954)

Single configuration

Double configuration

Double-Double Bailey Bridge (Juba Bridge, Juba, South Sudan, 2007)

Single configuration

Double configuration

Double Story with Link Reinforcement Set MGB used for Disaster Relief

Single configuration of 700XS panel (1973)

Double configuration of triangular panels (1990)

Triple-Single Acrow Bridge (Concepcion, Chile, 2011)

Mabey-Johnson Bridge for Disaster Relief (Angola, 1999)

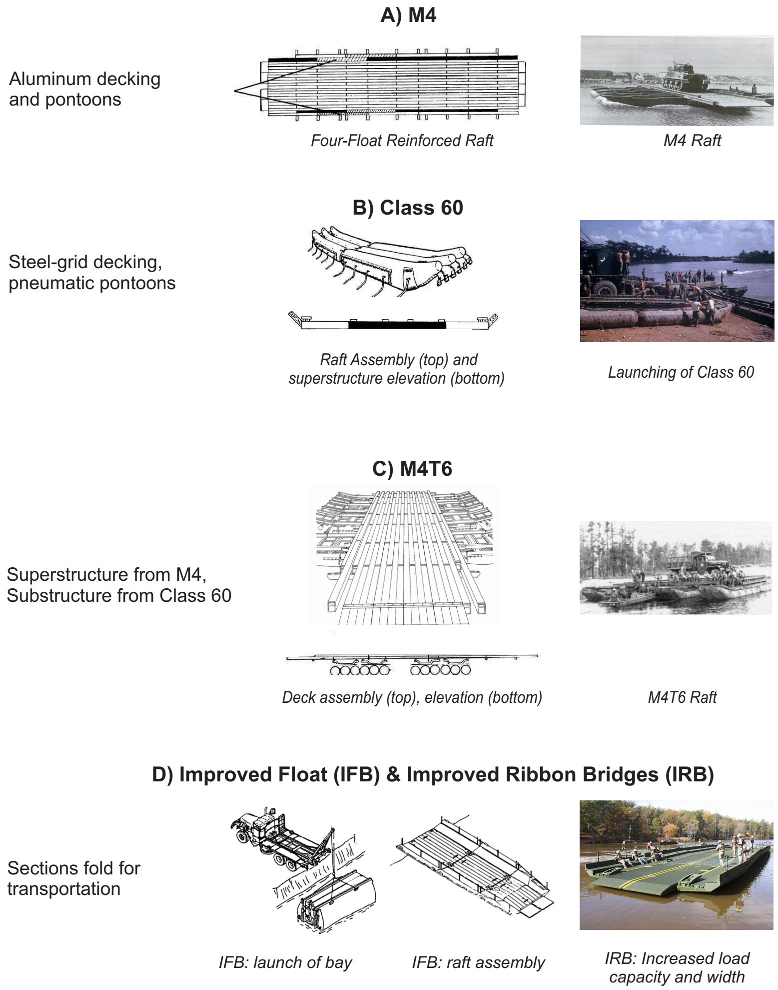
FIG. 1. Comparison of Rapidly Erectable Gap Crossing Bridge Systems. Photograph sources from top to bottom: Photograph by Oliver White, with permission from Structurae Website; Photograph by DEMOSH, with permission from Structurae Website; WFEL 2011, in process of obtaining permission; Photograph by Thrall; Image courtesy of Mabeybridge.co.uk.

A) M60A1 Armored Vehicle Launched Bridge

B) Dry Support Bridge

C) Composite Army Bridge

FIG. 2. Vehicle-Launched Bridges. Photograph sources from top to bottom: Photograph courtesy of U.S. Navy; WFEL 2011, in process of obtaining permission; Kosmatka 2011, in process of obtaining permission.



Four-Float Reinforced Raft

M4 Raft

Raft Assembly (top) and superstructure elevation (bottom)

Launching of Class 60

Deck assembly (top), elevation (bottom)

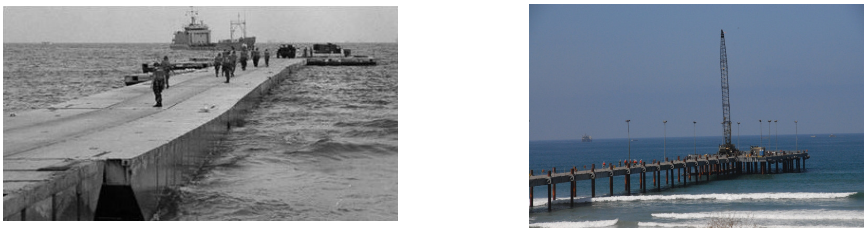
M4T6 Raft

IFB: launch of bay

IFB: raft assembly

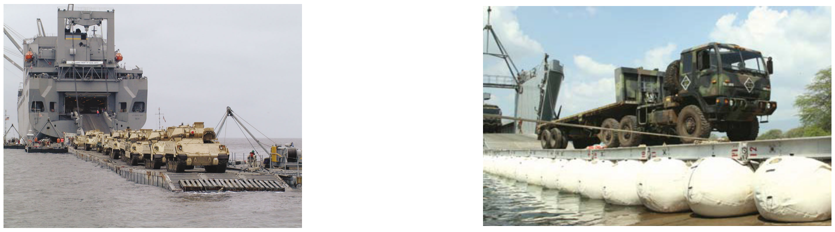
IRB: Increased load capacity and width

FIG. 3. Floating Solutions. All schematics courtesy of the U.S. Army. Photograph sources from top to bottom: Photograph courtesy of the U.S. Army; Photograph courtesy of 46th Engineer Battalion, with permission; Remaining two photographs courtesy of the U.S. Army.



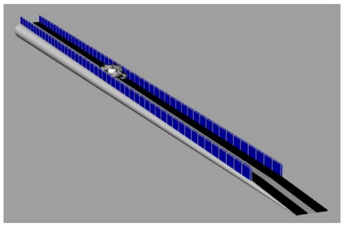
A) Modular Causeway Systems

B) Navy Elevated Causeway System



C) Improved Navy Lighterage System

D) Lightweight Modular Causeway System



E) MOSES

FIG. 4. Causeway Systems. Photograph sources from left to right, top to bottom: Photograph courtesy of U.S. Army; Photograph courtesy of U.S. Army; Photograph courtesy of U.S. Navy; Deming 2009, with permission from Army Sustainment; Mallen and Testerman 2008, courtesy of the U.S. Navy.