CONCRETE BRIDGE DEMOLITION METHODS AND EQUIPMENT

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ABSTRACT: The transportation infrastructure in the U.S. is maturing rather rapidly, leading to a shift of work and expenditures from new construction to maintenance, rehabilitation, retrofit, or even replacement of the existing system. Therefore, bridge demolition is increasingly becoming an important issue, as more bridges reach their service life and require rehabilitation or replacement. Furthermore, as the capacity of bridges and highways are reached, partial or total removal of bridges become necessary to allow for widening of the highway underneath the bridge or for widening the bridge itself to increase the capacity of the transportation system. Therefore, this paper addresses an important topic. It first discusses the factors affecting the selection of a bridge demolition technique. Then, the paper lists and describes a number of techniques and equipment employed in concrete bridge demolition along with discussions of actual bridge demolition projects and experiences. Finally, the paper outlines and discusses some safety issues related to the bridge demolition process.

INTRODUCTION

As the transportation infrastructure in the U.S. matures, the work and expenditures shift from new construction to maintenance, rehabilitation, and retrofit of the existing system. It is currently estimated that approximately 50% of all funds spent in the transportation area go directly for construction, maintenance, and rehabilitation of the pavements ("Keeping" 1988). As maintenance and rehabilitation increase, the percent of funds allocated to the pavements increases (Brecher 1995). One challenge in addressing the needs of transportation infrastructure works is the increased demand on highways and bridges due to the expansion in population. This increased demand led to the need for widening a number of major highways and bridges to increase the capacity and alleviate traffic congestion. This meant that a number of overpass bridges had to be demolished to allow for the expansion of the highways underneath. Furthermore, many bridges will also need to be widened to add extra lanes, creating a need for partial demolition and reconstruction. Moreover, many bridges in the country need retrofit work to increase their resistance to natural phenomena such as earthquakes. Therefore, demolition methods and equipment are increasingly becoming important issues when transportation infrastructure rehabilitation and maintenance programs are discussed. This paper provides an overview of such methods and equipment.

FACTORS AFFECTING SELECTION OF BRIDGE DEMOLITION METHODS

Bridge demolition projects typically involve the use of one or more of the demolition methods discussed in this paper. The choice of what demolition method(s) to use on a particular project depends on the following factors: (1) Financial; (2) time limits imposed on a project; (3) the strength and quality of the concrete; (4) the shape, size, and accessibility of the structure; (5) the amount of concrete to be removed; (6) environmental concerns, including noise, dust, vibrations, and debris; (7) worker safety and public safety; (8) possible recycling of concrete; and (9) removal, transport, and disposal of debris.

On bridge demolition projects, preventing inconvenience to the public is often of prime concern. Keeping lanes open during demolition, or a speedy demolition and removal of a bridge structure to prevent traffic problems on roadways running below the structure, may be factors that control the choice of demolition methods. Restrictions on noise, dust, or vibrations may be imposed on demolition projects in urban areas. Bridges or roadways crossing environmentally sensitive waterways may need to be removed using cleaner methods, which do not create debris. These are only a few of the examples that will be discussed in the paper.

DEMOLITION METHODS AND EQUIPMENT

In this section, demolition methods and equipment available for the full and partial removal of reinforced concrete bridges and elevated roadways are provided. The demolition of other types of structures is also discussed, however, as potential techniques for bridge projects. The section describes the following methods.

- machine-mounted demolition attachments
- hydrodemolition
- blasting and miniblasting
- sawing and cutting
- ball and crane
- splitting
- jackhammers
- thermal demolition.

Each method will be discussed along with its advantages and disadvantages. Then, example projects will be highlighted and described. Table 1 provides a summary description of these methods.

Machine-Mounted Demolition Attachments

Two methods, hydraulic hammers and crushers, are discussed and a description of sample projects employing these methods is provided.

Hydraulic Hammers

The mounting of hammers on excavators has allowed for the use of much larger hammers than traditional hand-held

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TABLE 1. Concrete Bridge Demolition Methods Summary

Method (1)	Applications (2)	Production (m^3/h) (3)	Advantages (4)	Disadvantages (5)
Machine-mounted demolition attachments				
Hydraulic hammers	Demolition of bridge decks, peers, slabs, and pavements	1–95	High production rate, greater mobility, operable in inclement weather	Noise, dust, and vibration
Whiphammers	Bridge deck removal	6–17	High production rates	High energy input
Crushers	Full and partial bridge removal	Up to 2	No dust, low noise, no vibrations, great mobility, operable in inclement weather, rapid and safe cutting of rebar	—
Hydrodemolition				
Nonabrasive water jet cutting	Partial removal of deteriorated concrete in bridge decks	1.4–4.3	Minimum labor, low noise, no dust, high production rate, no vibration, remaining concrete surface irregular allowing good bonding to new concrete	Rebar shadow problems, cost, needs large quantities of water, and disposal of the water that is mixed with debris
Abrasive water jet cutting	Partial removal of deteriorated concrete in bridge decks	—	No dust, low noise, minimal vibration, and very accurate cutting	Cost, dangerous due to the high pressures used, large quantities of water are needed, and disposal of the water that is mixed with debris
Blasting and miniblasting	Full and partial bridge removal	Not applicable	Speed, short durations of noise and dust	Dust, noise, vibrations, flying debris, and dangerous
Concrete sawing and cutting	Partial removal of deteriorated concrete	0.07–0.6	No dust, no vibration, and produces clean edges	Difficulties arise around rebar, cost
Splitting				
Mechanical splitters	Full and partial bridge removal	For both methods, rate depends on hole pattern, hardness of concrete, and orientation of rebar	No vibration, inexpensive, little dust, remaining concrete undamaged, and can be used underwater	Time consuming and requires the use of breakers to expose rebar
Chemical splitters	Full and partial bridge removal		No vibration, no noise, safe, and nonexplosive	More expensive than mechanical, requires more time
Jackhammers	Partial removal of deteriorated concrete in bridge decks	0.03	Easy to use	Slow, noise, dust, and remaining concrete and rebar may be damaged
Thermal Boring and Cutting	Method is new with potential applications in the partial removal of concrete	Cutting speed is 20–40 cm/min and depends on quality of concrete, type of aggregates, amount of rebar, and skill of operator	No vibration, low noise, can be used in places that are not easily accessible, and can be used underwater.	Cost, fire hazard, and generates large amount of fumes
Ball and crane	Bridge removal	—	Safety of project workers, simplicity of method	Control of the swing, dust, noise, and vibration

hammers, as well as offering great mobility in operating these attachments. Hydraulic hammers are rated in terms of impact energy measured in joules (foot-pounds). For example, a class 125 hammer delivers 169 J (125 ft-lb) of impact energy (Koski 1993). Smaller hammers, such as a class 125 or class 150, weigh 61–91 kg (135–200 lb) and deliver 450–1,000 blows per minute (bpm). The tool's diameters range from 2.54 to 5 cm (1 to 2 in.). The smaller hammers require an oil supply of 0.0076–0.0228 m^3/min (2–6 gal./min) at pressures of 10,343–13,790 kN/m^2 (1,500–2,000 psi) (Koski 1993). A larger hammer, class 10,000, weighs 4,409–5,227 kg (7,500–11,500 lb) and delivers 250–500 bpm. It has a tool diameter of 17.78 cm (7 in.). A class 10,000 hammer requires an oil supply of 0.228–0.323 m^3/min (60–85 gal./min) at pressures of 15,169–18,617 kN/m^2 (2,200–2,700 psi) (Koski 1993).

The smaller hammers are adequate for demolishing bridge decks, pavements, slabs, and unsupported concrete. On the other hand, larger hammers are for thicker, highly reinforced concrete members, such as bridge piers and abutments (Koski 1993).

It is vital that the hammer and excavator be properly matched. Smaller hammers (e.g., class 125 or 150 hammer) can be mounted on a miniexcavator, backhoe-loader, or skid steer loader. A class 10,000 hammer requires an excavator weighing from 45,455 to 68,182 kg (100,000 to 150,000 lb). A hammer that is too heavy can damage an excavator and a hammer that is too small can unintentionally be damaged by an excavator operator.

Depending on hammer size, concrete removal rates vary from 7.65 to 765 m^3 (10 to 1000 yd^3) per 8-h day for unreinforced concrete, and 9.95–573.75 m^3 (13–750 yd^3) per 8-h day for reinforced concrete (requiring larger hammer sizes as previously mentioned) (Hudgins 1987). Pneumatic hammers (powered by compressed air) are also available, though the range of sizes is much smaller. The pneumatic hammers range in size from 542 J (400 ft-lb) (weighing 450 lb or 205 kg, and delivering 1,100 bpm) to 2,710 J (2,000 ft-lb) (weighing 1,640 lb or 745 kg, and delivering 600 bpm) ("Removing" 1991).

The advantages of hydraulic hammers include high productivity, greater mobility including underwater use and remote control operation, operable in inclement weather because the operator is shielded inside the excavator cab, and reduced physical stress on operating personnel in comparison with conventional hand-held hammers. On the other hand, there are a number of disadvantages in using hydraulic hammers. They can generate large amounts of noise, dust, and vibrations and may be restricted in areas of limited space. Hammers, therefore, may not be suited for every project.

Whiphammers

A whiphammer is a truck-mounted percussive hammer, hydraulically operated and attached at the end of a heavily restrained leaf spring arm ("Removing" 1991). The concept behind its operation is that the hammer is raised and swung downward adding to the force with which the hammer strikes the concrete. The swinging resembles a whiplike spring that the hammer is named after. There are six head hammers available ranging in the number of blows per minute from 35 to 40. The energy produced by each blow is equal to 405,000 J (300,000 ft-lb) ("Removing" 1991). One of the six hammer heads is specifically designed for bridge deck demolition, whereby penetration is avoided to protect the beams from damage. Production rates for bridge deck removal ranges from 37 to 110 m^2/h (400 to 1200 ft^2/h) or 6 to 17 m^3/h (200 to 600 ft^3/h) for a 15 cm (6 in.) thick deck ("Removing" 1991).

The main advantage of whiphammers is their high production rates. However, they require a high energy input per blow to produce this high production rate.

Crushers

Crushers effectively demolish concrete (or cut reinforcement) by applying opposing forces on either side of a concrete member (or reinforcement). Maximum crushing forces of these attachments can exceed 3,113.6 kN (350 tons) (Koski 1993). Crushers range in size, from small hand-held units weighing 39 kg (86 lb), to large rig-mounted units weighing in excess of 3,364 kg (7 tons) ("Removing" 1991). These "jaw-like" attachments may include large cracking jaws used to remove large sections of concrete, shear jaws to cut through concrete and reinforcement (some are capable of shearing through closely spaced number 18 bars), and pulverizing jaws that are used to separate the concrete from the reinforcement. These attachments can be mounted on an excavator boom or the end of a crane rope, allowing for demolition of areas not reachable by excavator booms (Barth 1993). Some models allow for the crusher head to rotate on a turntable 360°, leading to even greater mobility (Koski 1993). Production rate ranges from 1 to 2 m^3/h (35 to 70 ft^3/h) ("Removing" 1991).

The advantages of crushers include: no dust; low noise level; no vibrations; high productivity; great mobility; operable in inclement weather; utilization for loading debris into trucks for removal; rapid and safe cutting of reinforcement; and effective ability to separate concrete from steel, allowing for recycling of both materials.

Successful Hammers and Crushers Projects

Hydraulic hammers mounted on miniexcavators were used to remove concrete on a bridge project in New Jersey. The working space was only 1.74 m (5 ft) wide, with much of the work to be done during winter months. The two miniexcavators used were able to operate within this space using 678 J (500 ft-lb) hammers (hand-held hammers supplemented the work done by the excavator-mounted hammers). During inclement weather, when it was impossible for hand-held hammer operators to work, the excavators were able to keep operating (Small 1987).

The 1989 Loma Prieta Earthquake damaged many bridge structures in the San Francisco area. Blasting was not permitted because these bridges were located in the heavily populated downtown San Francisco, often within feet of other buildings. Hydraulic crushers allowed for the quick and careful removal of these structures (Abudayyeh 1997; Barth 1993). Crushers were also used to separate the steel reinforcement from concrete, allowing the contractor to recycle the reinforcement.

A bridge near Hamilton, Ontario, Canada, was successfully removed using both excavator-mounted hammers and hydraulic shears. The 2,923 m (8,400 ft) long bridge was removed by separating the concrete from the reinforcement using four excavator-mounted hammers, followed by two hydraulic shears that cut the reinforcement into pieces small enough to fall through the bridge superstructure. The shears were also used to cut the 49 m (140 ft) high guardrail, a job that would normally have been performed manually with a cutting torch (a rather long and dangerous job). With operating personnel inside of an excavator cab, weather did not interfere as much, and the job was finished faster, safer, and with less personnel (Shears 1986).

On another project, extensive shoring was needed to support the weight of steel girders as well as the weight of removal equipment, while piers originally supporting the structure were removed. Blasting and hammering were used to demolish piers supporting Chicago's Dan Ryan Expressway. The project called for the complete removal of 72 existing piers and partial removal on many others. Piers taller than 10 m (30 ft) were first blasted with explosives to expedite removal with an excavator-mounted hammer. The excavator used for removing the taller piers featured a three-piece boom that enabled the boom-mounted hammer to reach more than 17 m (50 ft) high. The smaller piers were removed using either a 9,214 J (6,800 ft-lb) or a 5,149 J (3,800 ft-lb) hydraulic hammer. The concrete deck was removed prior using a truck-mounted whiphammer with false decking installed between the bottom flanges of the girders to catch the debris that was later removed ("Bridge" 1988).

Hydrodemolition

Two methods, nonabrasive and abrasive water jet cutting, are discussed and a description of sample projects employing these methods is provided.

Nonabrasive Water Jet Cutting

High-velocity, high-pressure water jets have been used to demolish both deteriorated and sound concrete. Modern machines can be programmed to remove as much or as little concrete as required. This method is used for partial concrete removal, mainly to remove deteriorated concrete in bridge decks caused by de-icing salts. Deicing salts cause reinforcement corrosion that in turn leads to fracturing, delamination, and spalling of the concrete. Hydrodemolition is being used more frequently in lieu of hammering for reasons that will follow.

Hydrodemolition equipment consists of water-pumps, high-pressure hoses, high-pressure water nozzles, and a mobile housing unit for the water nozzles. A water source and filtration system to prevent wear on the equipment are also required along with a system to remove the used water and debris. The hydrodemolition unit removes concrete by blasting it with high-velocity jets of water. The depth of removal depends on the strength of the concrete and other factors that will be forthcoming. Deteriorated concrete is easily removed by hydrodemolition, whereas dense, homogeneous concrete is not ("Removing" 1991).

The first modern hydrodemolition equipment was developed by FIP Industriale S.P.A. of Sevazzano, Italy, in the late 1970s. The system was first used in the U.S. in the mid-1980s. A high-velocity, high-pressure water nozzle is housed in a robot that moves across a concrete slab. The nozzle(s) move back and forth on a transverse track allowing for a full width movement of about 6 ft (Bradley 1988). The microprocessor-controlled Hydrodemolisher from FIP Industriale can be programmed to cut to any depth, removing as little or as much concrete as needed. The Hydrodemolisher removes varying amounts of concrete by adjusting how quickly the nozzle moves and how fast the mobile unit moves forward ("Hydrodemolition" 1987). The Conjet concrete removal system from Atlas Copco. also consists of a high-pressure nozzle (117,215 kN/m^2 or 17,000 psi) housed in a tire-mounted, microprocessor controlled robot. A diesel-driven, high-pressure pump, at a remote location, pumps water through high-pressure hoses to the Conjet unit ("Hydro-demolition" 1988; Bridge 1986). The third system, called NLB's Spin Jet Concrete Buster, uses rotating jets (the nozzle moves in a circular path while moving transversely). Two 250-hp pumps are used to supply pressures of up to 137,900 kN/m^2 (20,000 psi) to the hydrodemolition unit.

In some cases, after concrete removal by a hydrodemolition unit, an inspection is performed to determine if any deteriorated concrete remains. If so, the removal procedure is repeated ("Hydro-demolition" 1988). A clean-up system must be in place during hydrodemolition to remove the debris and slurry (concrete/water mixture). The recommended clean-up procedure is to vacuum immediately behind the hydrodemolition unit, followed by flushing of the deck with clean water and subsequent vacuuming. This system prevents the concrete/water slurry from sticking to the remaining concrete and minimizes the formation of rust on exposed reinforcement. Production rates range from 9 to 28 m^2/h (100 to 300 ft^2/h) or 1.4 to 4.3 m^2/h (50 to 150 ft^3/h) ("Removing" 1991).

The advantages of hydrodemolition over conventional hammering include the following ("Hydrodemolition-harnessing" 1988; "Hydrodemolition" 1988).

1. Minimum labor resulting in reduced cost.
2. Low noise level and no dust.
3. Greater production rate, resulting in faster project completion and less disruption of traffic.
4. No vibrations that result in no microcracking in the remaining concrete.
5. Reinforcement is cleaned of scale and rust.
6. The surface of concrete remaining after hydrodemolition is irregular, allowing for a good mechanical bond between the old concrete and the new overlay.
7. Hydrodemolition removes less sound concrete than hammering does.

One difficulty encountered with some hydrodemolition machines is "rebar shadows." This can occur in situations where the removal of concrete from around the reinforcement is called for. The reinforcement can act as a shield, thereby not allowing for the removal of the concrete below the bar. It is noted, however that this phenomenon does not occur with all machines ("Removing" 1991). Probably the biggest drawback to using hydrodemolition is cost. The modern, sophisticated hydrodemolition machines can cost in excess of $500,000. Hydrodemolition is therefore only economical on rather large removal projects ("Removing" 1991). A second disadvantage of hydrodemolition is the need for large quantities of water for use in the demolition. A third disadvantage is the need to safely dispose the water that is mixed with debris during the demolition process.

Abrasive Water Jet Cutting

Reinforced concrete can be cut by mixing an abrasive in an ultra-high-speed stream of water, allowing for easy dismantling of the structure. The abrasive water jet cutting system consists of a water supply, ultra-high-pressure water pumps, ultra-high-pressure hoses, an operating board to control the cutting operation, a device to enable movement of the cutting nozzle, an abrasive supply device, and an ultra-high-pressure cutting nozzle (Konno 1988). Abrasives are classified into three groups: Mineral, metal, and artificial. The cutting nozzl operates with water pressures in excess of 214,325 kN/m^2 (35,000 psi), delivering 0.0141–0.0209 m^3/min (3.7 to 5.5 gal./min) (Konno 1988 and Matsushita 1988).

An important cutting parameter is the standoff (spacing between the nozzle and the object to be cut). Tests were performed in Japan to determine the optimum standoff for cutting, and it was found to be 0.95 cm (3/8 in.) (Konno 1988). Another important issue is whether to make the cut using one pass of the cutting nozzle at a low cutting speed (speed that the cutting nozzle is passed over the member to be cut, not the speed of the water coming out of the nozzle), or to make several passes at a higher speed. It was concluded that for members less than 30 cm (12 in.) thick one pass would be optimum. Whereas for members thicker than 30 cm (12 in.), several passes would produce better results (Konno 1988).

The advantages of abrasive water jet cutting include: no dust, low noise level, minimal vibrations, and very accurate cutting (Matsushita 1988). On the other hand, this method can be extremely dangerous to operating personnel due to the high pressures used. Additionally, the equipment used in this method is expensive and the durability of the equipment is poor due to high water pressures and abrasives, large quantities of water are needed, and the disposal of used water and debris needs to be controlled.

Successful Hydrodemolition Projects

The Hydrodemolisher from FIP Industriale was used to remove deteriorated concrete from bridge decks along Interstate Highway 80 in northern New Jersey. The contractors had originally planned to use pneumatic hammers followed by sandblasting to clean the reinforcement. Because of the time constraints imposed on the project, however, hydrodemolition was used instead. The Hydrodemolisher removed up to 2 m^3/h (60 ft^3/h) of concrete, allowing the contractor to complete the project 50 days ahead of schedule and thereby earn a bonus of $10,000/day, while allowing three of four lanes of traffic in each direction to remain open (Bradley 1988).

A contractor removed deteriorated concrete from a bridge deck in East St. Louis, Ill., using the Conjet concrete removal system from Atlas Copco. Conventional jackhammering was limited to daytime hours only due to nighttime noise limitations and therefore, hydrodemolition was chosen for the project. The Conjet unit was operated by two men working two 8-h shifts/day. A conventional jackhammer crew would be limited to an 8-h day, not only because of noise restrictions, but also because of the physical limitations of the operating personnel (hammering is extremely tiring). The total project time was cut in half by using hydrodemolition (Bridge 1986).

Cost was the primary reason hydrodemolition was chosen for a bridge rehabilitation project in Indiana. A one-year study by the Division of Toll Bridges concluded that partial demolition followed by resurfacing would cost one-fourth the amount of complete deck replacement ("Hydro-demolition" 1988). The Atlas Copco. Conjet unit was utilized to perform the concrete removal. The unit was operated 24 h/day, 6 days a week, with the three-man operating teams working 12-h shifts. The use of Hydrodemolition was expected to save the Indiana Department of Highways an estimated $500,000, as well as allow for speedy completion of the project with a minimal interference to traffic flow on valuable revenue-producing toll bridges ("Hydro-demolition" 1988).

A system developed by the National Liquid Blaster was also used to remove deteriorated concrete, to depths of 2.54–15.24

cm (1–6 in.), from bridge piers and columns. The system operates at pressures up to 137,900 kN/m^2 (20,000 psi). The units were mounted on a trailer towed by a pickup truck. Water was pumped by a 170-horsepower engine from a 19 m^3 (5,000 gal.) watertank also mounted on a trailer. The applicators (water nozzles) were hand-held, which caused some difficulty in keeping operating personnel dry and safe from flying debris ("Water" 1988).

Blasting and Miniblasting

Blasting is an effective method for both full and partial demolition of concrete structures. Blasting uses rapidly expanding gases, confined in a series of boreholes (it should be noted that the terms borehole, drill hole, and shot hole, which appear in this section, are used interchangeably), to produce fracturing of the surrounding concrete (Hudgins 1987). Blasting has been used for years as a method of complete structural removal. It can also be used for localized cutting and partial demolition of concrete structures by carefully controlling the blasting process.

Blasting is an immensely complex process. Performance, thus, has always been based on experience and the use of empirical formulas and parameters that govern the results of blasting (Molin 1982; Lauritzen 1988). Such parameters include the following.

1. Concrete parameters:
   a. Thickness of the member.
   b. Strength and quality of the concrete.
   c. Concentration and location of reinforcement.
2. Explosive charge parameters:
   a. Strength of the explosive.
   b. Coupling ratio that is defined as the ratio of drill-hole diameter to explosive diameter. As the coupling ratio increases, there is a considerable drop in the effectiveness of the explosive, but also a reduction in unwanted damage to the surrounding environment.
   c. Stemming, which is the closure of the hole using some material to confine the gasses resulting in higher pressures and better crack development. Materials typically used for stemming are clay, sand mixed with plaster, or well-graded, compacted sand.
   d. Interaction between the charges, whereby detonation of the individual drill-holes is delayed, meaning that individual holes are detonated at intervals normally ranging from 20–30 ms. This delayed detonation allows for the control of vibrations as well as controlling the extent of flyrock (debris) projection (Lauritzen 1991).
3. Geometric parameters:
   a. Burden.
   b. Spacing of the charges.
   c. Diameter and depth of drill hole.
   d. Constriction.

Explosives can be either mild or high explosives, depending on their blasting velocities. Mild explosives have velocities as low as 30 m/s, whereas high explosives have velocities of 4,000–7,000 m/s (Lauritzen 1991). There are four major classes of explosives ("Explosives" 1987).

1. Dynamite: This has the advantages of being good to excellent for water resistance as well as being predictable and reliable. Dynamite comes in a wide range of small- and medium-diameter cartridges of different lengths, which makes it possible to carefully control the amount of explosive placed in a drilled hole. Free-flowing explosives can fill in cracks, leading to a hazardous buildup of the charge.
2. ANFO: This is a combination of ammonium nitrate and fuel oil. It is generally used in dry applications, although a wet-service pack is also available. ANFO is very economical and effective but, because of its free-flowing form, a hazardous buildup can occur. Therefore, ANFO is not used under tightly controlled conditions.
3. Slurries: This consists of water-containing chemical mixtures that are either water gels or emulsions. Water gels contain oxidizing salts and fuels that are dissolved in water. Emulsions are fine droplets of oxidizing salts and water surrounded by a fuel mixture of wax and oil. Slurries are available in plastic or paper cartridges of small and medium diameters, or in bulk. Slurries offer performance and reliability approaching that of dynamite.
4. Emulsions/ANFO blends: This consists of ANFO mixed with varying percentages of concentrated high-velocity explosive, such as emulsion. Varying degrees of water resistance, velocity, density, borehole gas pressure, and cost, can be obtained with different mixtures. Emulsions/ANFO blends are available in film cartridges or in bulk.

Most initiation systems (detonation of the explosive) are of the delay type, whereby the detonation of individual holes is lagged so that vibrations and the extent of flyrock projection can be controlled. Electrical initiation systems are quite common; they are cheap, simple, and reliable ("Explosives" 1987). An advantage of the electrical system is that the circuits can be tested prior to actual firing. Conventional electric delay blasting systems offer 30 delay periods, which permits the firing of 30 individual holes. The timed firing interval between individual holes is normally 20–30 ms. Nonelectrical initiation systems are also available.

Careful and controlled blasting, using minimal explosives for partial concrete removal is referred to as miniblasting. When properly executed, miniblasting can be an effective means of removing concrete without damaging the remaining concrete and the surrounding environment (Lauritzen 1991). High explosives are used for this type of removal. High explosives rip the concrete from the reinforcement more cleanly than mild explosives.

The main advantage of full-blasting is speed, which means that traffic is not tied up for long. Other advantages include short durations of noise and dust. The advantages of miniblasting are its effectiveness in areas with closely spaced reinforcement unlike conventional hammering, and with this method a large section can be removed in one piece for later pulverizing in a controlled environment, making it possible to avoid the environmental problems usually associated with demolition (Lauritzen 1991). On the other hand, some of the disadvantages of blasting include: dust, noise, vibrations, flying debris, and the inherent danger associated with blasting.

Successful Blasting Projects

Blasting has been used in Germany quite extensively to remove bridges crossing over roadways. Blasting causes traffic tie-ups (and detours) to relatively short periods of time, which are planned when traffic is light (Roller 1988).

Explosives were used on the Sunshine Skyway Bridge (Tampa Bay, Fla.) demolition project, which called for the removal of 61,200 m^3 (80,000 cu yd) of concrete and 6,182,000 kg (6,800 tons) of structural steel (Terpening 1992). Concrete decks, hand railings, etc., were removed using concrete veneer saws, hydraulic shears, and hoe rams. The steel truss portion of the bridge was cut into pieces using explosives. The concentrated explosive charges burned through the steel much like a high-speed cutting torch. The pieces were then removed using barges. The concrete piers were demolished in two stages using a high quantity of explosives packed into drill holes. The blast, which sent concrete debris flying 44 m (125 ft) into the air, effectively fragmented the concrete. To prevent any harm to marine life, a special precaution was taken prior to blasting the piers below the water line. This consisted of detonating small charges to scare away the marine life.

Concrete Sawing and Cutting

Two methods are discussed here: (1) blade saws and (2) diamond wire cutting. Blade saws are generally used to cut concrete structural members (usually bridge decks) into large pieces, which can then be easily removed using an overhead crane. Wet-cutting diamond blades are the most common type of blades used to cut concrete. Diamond blades are made by welding or brazing diamond segments to the perimeter of a steel disk (Tips 1987). The diamond segments are made of diamond particles held together by a metal bond. Saws that will cut different types of concrete are made by varying the composition of this metal or by varying the type, size, and concentration of diamond particles (Tips 1987). A water source is required to cool the blade during the cutting operation, thereby preventing overheating of the blade, which leads to detachment of the diamond segments. Typically, 0.0076–0.019 m^3/min (2–5 gal./min) of water is required. When cutting reinforcement, it is recommended that the blade and the pressure on the blade be reduced, and the flow of water increased ("Removing" 1991). Dry cutting diamond saw blades are also available, but should be used on low-horsepower saws. The operator can more easily control the cutting speed (and thus the amount of heat generated) with a low-horsepower saw. Large carbide-tipped cutting wheels are also available (Wallace 1985). It is worth noting that training of operating personnel is essential because of the high cost of replacing diamond blades.

Diamond wire cutting is a technology that originated in Italy approximately 22 years ago. It was imported and regularly used in cutting reinforced concrete in the U.S. in the early 1980s (Hulick 1989). The most common type of diamond cutting wire consists of industrial diamonds electroplated to a steel bead that is strung onto a wire rope. The beads are separated by partially compressed steel springs (spacing can also be achieved using plastic). "Crimps" are used to limit sliding of the beads on the rope due to constant spring extension and compression. A limited amount of movement is advantageous, however, in that it prevents shock loads to the wire and driving equipment when the beads catch on sharp edges (Hulick 1989). This system allows for wires of any length to be fabricated. Wires as long as 139 m (400 ft) have been used, although 14–35 m (40–100 ft) wires are most common (Hulick 1989). Another diamond wire system consists of impregnated beads (also known as "siterized" beads). These beads have higher concentrations of smaller diamonds throughout the thickness of the bead. This allows for effective cutting of concrete with high concentrations of reinforcement. As the bonding matrix wears away during cutting, more diamonds are exposed. Production rates, which depend on the type of diamond wire used, the type of aggregate used in the concrete, and the size and concentration of reinforcement, range from 0.465 to 3.72 m^2/h (5 to 40 ft^2/h) or 0.07 to 0.6 m^3/h (2.5 to 20 ft^3/h) (Hulick 1989). To begin the cutting operation a 2.54–5.1 cm (1–2 in.) hole is drilled through the concrete and the wire is passed through. The wire is then joined together, using a steel coupling, and is placed on the drive wheel. A water source is required to cool the wire during cutting and to wash away the slurry created by the cutting operation. Precautions should be taken to protect personnel in the event a wire snaps.

The advantages of these methods are (Hulick 1989; Kemi 1988; and Tips 1987) as follows.

1. No dust because of the cooling water and low noise level.
2. No vibrations, thereby preventing damage to remaining structural elements.
3. Sawing leaves a clean, straight edge.
4. Allows for the cutting and subsequent removal of large, individual sections of a structure, thus, preventing the creation of large amounts of debris and allowing for efficient dismantling of a structure.
5. Diamond wire systems are effective regardless of the thickness of the cut or the amount of reinforcement.

The disadvantages of these methods are (Hulick 1989) as follows.

1. Diamond blade saws are limited in the depth of cut they can make (diamond wire systems are not).
2. Difficulties can arise using diamond blade saws when the blade comes in contact with reinforcement running parallel to the cut.
3. Some of diamond wire cutting system (e.g. the siterized bead) are expensive and the diameter of the bead is slowly reduced as the cut progresses.

Successful Blade Saws and Diamond Cutting Projects

Diamond blade saws and large carbide-tipped cutters were used to remove deteriorated sections of the Eisenhower Expressway in Chicago (Wallace 1985). These sections were subsequently replaced with full-depth patches. The diamond saws cut the perimeter of the sections to be removed, leaving the straight, smooth sides required by the project specifications. A large, 2.44 m (7 ft) diameter, carbide-tipped cutting wheel cut the sections into smaller pieces that could then be lifted o using a crane. The carbide-tipped cutting wheel was used in lieu of the diamond blade saws because a full-depth cut could be made on one pass using the carbide-tipped cutting wheel (the carbide-tipped cutting wheel can cut up to 79 cm deep). The diamond saws, with diameters of 46–66 cm (18–26 in.), needed two passes. The 46 cm (18 in.) saw would begin the cut and the 66 cm (26 in.) saw would take it to full depth. The carbide-tipped cutting wheel also left a 10 cm (4 in.) wide cut, allowing enough space to place a crane hook for subsequent removal.

Ball and Crane

In this method, a crane swings or drops a wrecking ball onto a structure, breaking the concrete into smaller pieces. It is usually necessary, however, to cut the reinforcement, using other methods, before the structure can be removed from the site. Wrecking balls typically weigh from 455 to 1,818 kg (1,000 to 4,000 lb), although they may weigh up to 6,136 kg (13,500 lb) ("Removing" 1991; Hudgins 1987). The "wrecking ball" does not need to have a spherical shape. Other shapes, such as brick and steel ingots, are fairly common.

To ensure safe operation of a crane using a wrecking ball, the National Association of Demolition Contractors recommends that the ball weight not exceed 50% of the safe load of the boom at maximum length or angle of operation, or 25% of the nominal breaking strength of the supporting line, whichever is less. The demolition ball should be attached using a swivel-type connection to prevent twisting of the load lin (Hudgins 1987). Most importantly, the crane operator must b highly skilled to ensure maximum safety during the demolition operation.

The advantages of ball and crane demolition include: safety of project workers, because they are not required to be inside the collapse envelope of the structure during the demolition operation (Chacos 1991), and simplicity of the operation. The disadvantages of ball and crane, on the other hand, relate to the control of the swing of the ball. Missing the desired target may tip or overload the crane and a wild swing-back of the ball may cause it to hit the boom. Obviously, care must also be taken when operating around power lines. Additionally, demolition using a ball and crane can create large amounts of dust, noise, and vibrations.

Splitting

Splitting methods are classified into two categories: (1) Mechanical and (2) chemical. Each of these categories are discussed next.

Mechanical Splitters

Mechanical splitting is accomplished using hand-held splitting tools that apply hydraulic pressure to concrete causing it to fragment ("Removing" 1991; Hudgins 1987). The splitting process involves drilling 2.54–5 cm (1–2 in.) holes in the concrete. Then, the splitting end of the tool, which is a steel wedge positioned between two hard metal shims called feathers, is inserted into each hole. Next, a hydraulic pressure is applied to force the wedge against the feathers, which expand and split the concrete. The force exerted by the feathers ranges from 1,100 to 3,650 kN (125 to 410 tons). Keys to a successful outcome are the hole patterns and controlling the direction of the break. Holes must be of the correct diameter and be straight to protect the feathers from damage. The direction of the break is controlled by properly aligning the feathers in the holes.

Several advantages of mechanical splitters include: there is no vibration, they are relatively inexpensive, produce little dust, the remaining concrete is left undamaged, and they can be used underwater. Their disadvantages include: it is a time-consuming process, and it requires the use of breakers to expose reinforcement for cutting.

Chemical Splitters

Chemical splitting involves using expansive agents that undergo a large increase in volume when properly mixed (Hinze 1994; "Removing" 1991; Yamazaki 1988; Hudgin 1987). These agents are placed in holes drilled in concrete in a predetermined pattern. Once the agents expand in the holes, the concrete splits. The chemical composition of these agents, which are sometimes called expansive grouts, consist of calcium oxide that expands when hydrated.

The advantages of chemical splitters include: they are non-explosive, there is no vibration or noise, and they are safe. Disadvantages of chemical splitters include: they are more costly than mechanical splitters or explosives, and it takes more time to complete a demolition job with chemical splitters than with mechanical splitters or explosives.

Jackhammers

Jackhammers are hand-held percussion tools used for the partial removal of concrete before repair or replacement. They are powered by air compressors, electricity, or gasoline engines. Jackhammers are classified by their weight and range from 9 to 44 kg (20 to 90 lb) ("Removing" 1991). As the compressed air flows through the hammer, it causes a piston to reciprocate at a speed ranging from 900 to 2,500 bpm. Production rates vary dependent on the quality and amount of concrete, the skill of the worker, and ease of access. A typical production rate for a 14 kg (30 lb) jackhammer operated on a horizontal surface is 0.5 m^2/h (5 ft^2/h) or 0.03 m^3/h (1 ft^3/h) ("Removing" 1991).

The main advantage of jackhammers is that they are easy to use. However, their disadvantages are that they are slow, noisy, and dusty, also any remaining concrete may be extensively microcracked and may damage remaining rebar and their bond to remaining concrete.

Thermal Demolition

Thermal demolition processes are fairly new techniques with potential applications to the partial removal of concrete bridges. They can be grouped into three categories ("Removing" 1991; Kasai 1989): (1) Thermal boring and cutting; (2) cracking and peeling; and (3) breaking and peeling. The following is a brief description of each category.

1. **Thermal Boring and Cutting**: In this category, a high temperature is used to heat and melt concrete. The heat is generated using flame, plasma, or laser beam. In the flame process (also known as thermit flame or thermal lance), a 13–17 mm (0.5–0.7 in.) o.d. pipe that contains iron or aluminum alloy wire is used. The alloys are ignited to obtain a high temperature of 3,000°C (5,400°F) and applied to the concrete. Concrete can be cut at a speed of 20–40 cm/min (8–16 in./min). The cutting speed depends on the quality of concrete, type of aggregates, the amount of reinforcement, operator skill, and the smoothness of discharge of the molten slag. The advantages of this method include no vibration, a low noise level, it can be used under water, it is not hampered by the presence of steel plates or steel frames, and it can be used in places that are not easily accessible. The disadvantages are that it is costly when compared to mechanical methods, molten slag may cause fire, and the process generates large amounts of fumes that require a good ventilation system.
2. **Cracking and Peeling**: In this category, concrete cover is removed by cracking and delamination occurs by electrically heating the reinforcing steel ("Removing" 1991; Kasai 1989).
3. **Breaking and Peeling**: In this category, concrete is broken by direct heating using electric energy. The heating energy is generated from either microwave or high-frequency waves, and high voltage ("Removing" 1991; Kasai 1989).

SAFETY ISSUES IN BRIDGE DEMOLITION

Demolishing bridge structures is an involved process that requires careful planning, execution, and inspection to establish and maintain a safe work environment (Abudayyeh 1997). The responsibility of safety lies on both the contractor and the owner. This section briefly summarizes some of the issues that need to be considered when developing a safety plan that addresses the needs of all parties involved in a demolition project. These issues include protecting workers and the public, protecting adjacent structures, and protecting existing utilities.

Protecting Workers and Public

To ensure adequate protection to the workers and the public, the contractor and the owner should do the following.

- Develop proper demolition plans showing the demolition sequence, staging, equipment location, restraints and falsework for structural stability, and traffic control. The demolition plan should include detailed engineering calculations showing load determinations and structural analyses.
- Develop a comprehensive "Code of Safe Practice" that

includes a plan for the use of personal protective equipment (hard hats, safety glasses, construction boots, tie-off, protective clothing, seat belts and canopies).
- Develop a maintenance plan for keeping all pieces of equipment on the job in good working condition for the duration of the project.
- Develop a dust control plan (such as using water sprays).
- Develop a plan to prevent debris from injuring the public and the workers (such as using debris nets).
- Develop a plan to protect the public from noise (such as monitoring work-hour schedules and noise levels).

Protecting Utilities

Two types of utilities may exist in the vicinity of a demolition project: (1) Underground and (2) overhead. Underground utilities may include gas mains, water pipes, and sewer lines. Overhead utilities may include the power and telephone lines electric lines. To protect underground utilities, a number of measures can be taken:

- Debris piles may be built on top of such lines to provide a cushion against impact from falling objects.
- Steel plates may also be used as covers to protect against impact.
- High-pressure water lines should be shut down within the demolition zone.
- No large debris object should be allowed to drop.

To protect overhead utilities, the contractor and the owner should work closely with the responsible agency to arrange for a temporary shutdown and removal of those lines in the immediate vicinity of the portion of the structure being demolished until the operation is complete. Accurate schedules should always be sent to utility agencies to minimize service disruption and inconvenience to the public.

Protecting Adjacent Structures

One of the major challenges during a bridge demolition project is how to protect adjacent structures. Some of these structures may be so close to the bridge that careful planning becomes extremely important to avoid damage or even collapse of such structures. Some of the measures that can be taken to ensure the protection of adjacent structures are as follows.

- All hinges on the spans of a bridge should be restrained using steel cables or rods to prevent a premature collapse of a bridge span by slipping off the hinge seat.
- All possible loads on a bridge should be analyzed to establish a safe loading range before demolition starts to ensure that spans do not become overloaded by debris and/or heavy pieces of equipment.
- All columns should be restrained by temporary column-restraining steel structures and/or cables to prevent the premature collapse of a column in the direction of adjacent structures.
- A vibration monitoring program may also be established to prevent vibrations from exceeding the maximum limits for adjacent structures.

SUMMARY AND CONCLUSIONS

Bridge demolition is an involved process that needs careful engineering and management. A number of demolition methods and equipment were described in the paper, providing an overview of how each method works and what type of projects it serves. The paper then discussed safety issues related to bridge demolition and how a plan should be developed to provide a safe work environment. Bridge demolition is becoming an increasingly important subject when dealing with transportation infrastructure rehabilitation and maintenance as more and more bridges and highways reach their design service li and become candidates for replacement, rehabilitation, and/or widening. More emphasis should be placed on engineering demolition projects to achieve a satisfactory outcome.

ACKNOWLEDGMENTS

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BEHAVIOR OF NONLINEARLY RESTRAINED SLENDER BRIDGE PIERS

By Giuseppe Mancini,[1] Francesco Martinez y Cabrera,[2] Marco Andrea Pisani,[3] Member, ASCE, and Antonino Recupero[4]

ABSTRACT: The load-carrying capacity of slender reinforced concrete piers depends on the horizontal retaining forces exerted by the bridge deck. The magnitude of these forces is a function of the behavior of the restraints connecting the deck to the piers and to the abutments, as well as of their evolution in the presence of increasing loads. A numerical method, that was developed to perform a geometrically and mechanically nonlinear analysis of the piers, is described in this paper. This method also takes into account the evolution up to failure of the behavior of the restraints. By means of computations on a large number of different restraint conditions on a real bridge, it is shown to what extent the restrain effects exerted by the bridge deck may affect the safety factor γ_f on the action side of the piers. Elastic-rigid restraints and sliding-rigid restraints are considered; both of them are able to stop after a predetermined displacement value, becoming infinitely rigid beyond this value.

INTRODUCTION

In the commonest standard of bridges and viaducts, in which decks and piers are structurally independent and mutually connected by restraints of various shapes, it is not easy to define the actual restraint conditions to which piers are subjected at their upper ends. Both the static scheme of the deck, in fact, which can be built as a series of statically determinate spans or a long continuous beam, and the geometry and the consistence of connecting elements generally require the taking into account of mutual restraint conditions, which are difficult to assess and are often characterized by nonlinear behavior (Menn 1990; Mancini et al. 1994). This applies, for instance, to the friction forces at sliding supports, and to the possible presence of end-of-travel stops in the deck and/or piers, with linear and nonlinear behavior, which are introduced to control the evolution of displacements according to predetermined laws.

The presence of such restraint conditions therefore plays a fundamental role in the definition of the safety of slender piers, in which, as is well known, even the intervention of weak restraint conditions can substantially modify the behavior of piers affected by second-order effects.

This paper proposes a method to verify the safety of slender piers with a nonlinear response from both the material and the geometric point of view. The concerned piers can be restrained at any section by either rigid restraints or restraints with a nonlinear response, and, at a single section, by a unilateral sliding-rigid restraint, able to stop after a predetermined limit displacement. The combined action of these two types of restraints in a common section of the pier makes it possible to obtain a nonlinear response system, which becomes infinitely rigid beyond a predetermined displacement (Fig. 1).

Presently the formulation of this proposal is limited to plane structural systems.

A numerical example points out that such restraints can increase the safety global coefficient of a pier from 1.2 to >7.

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METHOD OF ANALYSIS

The analysis process is inspired to the current trend in the field of finite elements (Cook 1981; Lui 1988; Zienkiewicz and Taylor 1989; Fertis and Keene 1990, Ghali 1993; Stallings 1993; Sun et al. 1993) and is carried out through an automatic computation method called FEM 2D, which takes into account only two types of elements:

1. The classical BEAM element (Fig. 2) behavior can be represented through the expression

$$\mathbf{r} = \mathbf{r}_{0a} + \mathbf{k}_e \cdot \mathbf{d} \quad (1)$$

where $\mathbf{r} = \{N_1\ M_1\ V_1\ N_2\ M_2\ V_2\}^T$ nodal internal action vector; $\mathbf{r}_{0a}$ = vector of actions, when the displacements are restrained; $\mathbf{k}_e$ = elastic stiffness matrix of the elemen and $\mathbf{d} = \{u_1\ \vartheta_1\ \delta_1\ u_2\ \vartheta_2\ \delta_2\}^T$ vector of nodal displacements.

2. A BOUNDARY element representing the sliding-rigid restraint, whose stiffness matrix has 1 × 1 dimensions and corresponds to the same stiffness of the restraint; the behavior of this element can be represented, by analogy to the previous one, in the form

$$\mathbf{r}^k = \mathbf{r}_0^k + \mathbf{k}_e^k \cdot \mathbf{d}^k \quad (2)$$

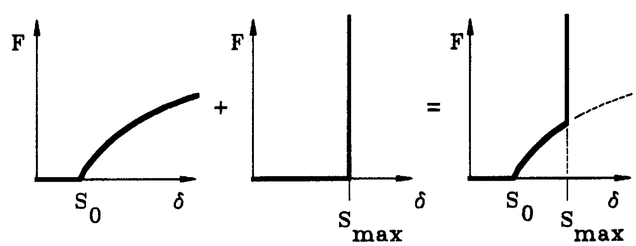

FIG. 1. Combined Effect of Two Types of Restraint

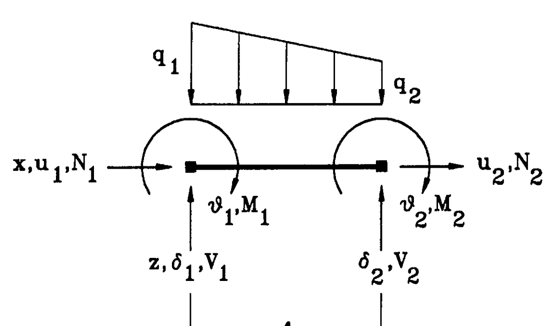

FIG. 2. Beam Element Used