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Green Demolition of Reinforced Concrete Structures: Review of Research Findings

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Abstract- The buildings and transportation infrastructures in the world are maturing rather rapidly, which lead to the maintenance, rehabilitation, retrofit, or dismantling the existing system become future trends rather than new construction. Therefore, concrete structure demolition is increasingly becoming an important issue, as more concrete structures reach their service life and require rehabilitation or replacement. Furthermore, as the bearing capacity of concrete structures are reached, partial or total removal of concrete structures become necessary to utilize the spaces of the cities widely and effectively, as well as to widen 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 concrete structure demolition technologies. Then, the paper lists and describes a number of traditional and green demolition technologies and equipment employed in concrete structure demolition along with discussions of actual structure demolition projects and experiences. Finally, the paper outlines and discusses some safety issues related to the structure demolition process.

Keywords: *green demolition; reinforced concrete; affecting factor; safety; pollution.*

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Green Demolition of Reinforced Concrete Structures: Review of Research Findings

Jing Zhu [α], Wenzhong Zheng [σ], Lesley H Sneed [ρ], Chonghao Xu [ω] & Yiqiang Sun [¥]

Abstract- The buildings and transportation infrastructures in the world are maturing rather rapidly, which lead to the maintenance, rehabilitation, retrofit, or dismantling the existing system become future trends rather than new construction. Therefore, concrete structure demolition is increasingly becoming an important issue, as more concrete structures reach their service life and require rehabilitation or replacement. Furthermore, as the bearing capacity of concrete structures are reached, partial or total removal of concrete structures become necessary to utilize the spaces of the cities widely and effectively, as well as to widen 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 concrete structure demolition technologies. Then, the paper lists and describes a number of traditional and green demolition technologies and equipment employed in concrete structure demolition along with discussions of actual structure demolition projects and experiences. Finally, the paper outlines and discusses some safety issues related to the structure demolition process.

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I. Introduction

As the structure and transportation infrastructures in the world matures, the work and expenditures shift from new construction to maintenance, rehabilitation, and retrofit of the existing system. Taking China as an example, some concrete structures, which still maintain their own strength enough. have a tendency to be demolished intentionally to utilize the spaces of the cities widely and effectively. According to statistics, these buildings have a life span of only 25 to 30 years. However, the average life span of buildings in Britain is 132 years, and that in the U.S. is 74 years[1].If we do not solve the critical problems as soon as possible, the consequences of 'short-lived buildings' are quite serious, which not only cause great waste of social resources (including economy, resource, labour, energy, time, etc), but also pose a threat to the human living environment. In these demolition works, explosives such as dynamite or heavy machines have been used, and sounds, vibrations and some other pollution are also caused[2]. Besides, the demolition of reinforced concrete structures in dense urban areas has great safety risks, and the impact of demolition accidents are extremely serious. Consequently, it is required to consider the safety and the prevention of pollution during demolition.

In addition, 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 in the U.S [3]. As maintenance and rehabilitation increase, the percent of funds allocated to the pavements increases [4].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 and so on. Therefore, traditional and green demolition methods and equipment are increasingly becoming important issues when buildings and transportation infrastructures rehabilitation and maintenance programs are discussed. This paper provides an overview of such methods and equipment. Advantages and disadvantages associated with each demolition technique are analyzed, and discusses some safety issues related to the buildings and transportation demolition process.

II. Background

The demolition industry has experienced radical transformation during the past 40 years, and it utilizes a variety of means for dismantling reinforced concrete structures. The use of jackhammers, saw cutting, wrecking balls, hydraulic excavator and water jetting are examples of traditional demolition methods (including manual demolition, mechanical demolition, blasting demolition, etc). Selective demolition is another method that has been developed. Each of these methods has

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advantages that make it useful for various applications [5]. It is sometimes the case, though, these methods are overall limited by rough management, low technical level, serious environmental pollution and insufficient research results about basic theories and core technologies. Therefore, chemical expansive agent and intelligent robot demolition technology have superseded crawler cranes and demolition balls. In addition to this transformation, the 'British Standard Code of Practice for Demolition', has been revised three times since its introduction in 1971. It started with CP94, which has been superseded by BS 6187: 1982 and currently by BS 6187: 2000[6]. It is the general trend to optimize the selection of suitable demolition technology and to develop innovative green and safe demolition technologies.

A case study of green demolition technique is to dismantle a hotel of Jiangsu in China. This green demolition project spent only 10 h to remove this 8,000 m2 concrete frame building, while traditional demolition technique would take 10 d in the same situation. Conversely, both transportation costs are also similar. As is well known, tipping fees pose a significant cost for demolition and deconstruction, and these fees can range from $65 to $80 per ton. But the 100% demolition waste was recycled and reused in this project. It should be noted that zero waste is disposed after green demolition. so the overall cost of disposal is saved. In addition, this green demolition project used hydraulic scissors, diamond saw, water pressure knife, dismantling robot, mobile crusher and other high-tech means to substitute the previous jackhammers, excavator, engineering blasting and other traditional means, to achieve no noise, no dust, no vibration and non-pollution demolition. The demolition waste was carried out to sort and process on site, and the building materials such as concrete, mortar and brick and so on were recycled. Moreover, this project develops "wisdom cloud" management system of the demolition waste disposal to detect the geographical environment of the demolition project and plan out the most reasonable junk traffic lines, and the vehicle trajectory can be real-time monitored, etc. What`s more, the generation and regeneration of demolition waste can also be fully digitized and transparent, and all work is ensured to process safety control, green environmental protection. Therefore, the demolition project acquires better effects of safety, green, environmental protection, high efficiency and recyclability.

III. Affecting Factors of Concrete Structure Demolition Methods

Concrete structure 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 structure demolition projects, safety is of prime importance among these key factors to consider. All movements of people within the structure should be along designated routes, and debris should not be all owed to accumulate to a weight greater than a floor can carry. When demolishing a structure from the top down, no supports at a lower level should be cut or removed until demolition at the upper level is completed[7]. Workers must always stand on a firm base while carrying out demolition. For another, 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.

IV. Traditional Demolition Technologies

For a long time, traditional demolition technologies (including manual demolition, mechanical demolition and blasting demolition) are the main methods of removing the reinforced concrete structures. Demolition methods vary according to building location, construction materials, disposal techniques and the ultimate demolition goal. Reinforced concrete structures should be dismantled step by step as construction works. Knowing which method or combination of methods to use for demolition of reinforced concrete structures is essential for a safe and profitable job as well as prevention of pollution demolition [2]. At present, hydraulic excavators with specialist attachments are used for almost every conceivable demolition work from dismantling the roof to breaking up and removing the foundations, replacing the once dominant crawler cranes and demolition balls. However, their use on demolition projects is not straightforward in practice due to complicated site conditions and other constraints. Selection of the best method or methods depends partly on time and money available and on the technological level [8].

There are many types of demolition techniques in the industry. Many of them are used together. Kasai et al [9] stated that the demolition techniques could be classified into eleven principles and mechanisms, while in code of practice for demolition BS 6187: 1998, the demolition techniques are listed into seven categories[5,10]. In this section, demolition methods and equipment available for the full and partial removal of reinforced concrete buildings and bridges are provided. This following information outlines the different types of traditional approaches and demolition services a modern demolition company such as Elder Demolition is likely to offer. The section describes the following methods.

- Demolition by hand
- Saw cutting
- Ball and crane
- Hydraulic excavator
- Water jetting
- Hydraulic splitter
- Thermal lance
- Explosive

Each method will be discussed along with its advantages and disadvantages. Then, example projects will be highlighted and described. Table I provides a summary description of traditional demolition technologies. The following discussion of conventional methods used is based primarily on their widespread application, and the techniques are provided by relational codes (including Code of Practice for Demolition of Buildings Year 2004), research and demolition experience.

Table 1: Summary of Traditional Demolition Technologies of Concrete Structures

Method	Applications	Production (m^3/h)	Advantages	Disadvantages
Demolitin by hand	Demolition of floor slabs, bridge, peers, and pavements	6～17	simple to operate, strong mobility, effective in narrow and localised place, precisely removal, well recycled materials	Noise, dust, and vibration, low efficiency, crowd tactics, high demolition cost
Saw cutting	Partial removal of deteriorated concrete, removal of free-standing walls, dismantlement concrete slabs and wall elements containing reinforcement	0.07～0.6	No dust, no vibration, and produces clean edges, easy to operate	Difficulties arise around rebar, slow and costly, noisy, blade wear, additional safety requirements and procedures of workers because of noise, cooling water needed to deal with
Ball and crane	Demolition of dilapidated buildings, silos and other industrial facilities, bridge removal	—	Workers safety, simplicity of the operation	Control of the swing, large amounts of dust, noise, and vibrations,substantial clear space and high clearance
Hydraulic excavator	Full and partial structure and bridge removal, isolated buildings	Up to 2	No dust, low noise, no vibrations, great mobility, operable in inclement weather, rapid and safe cutting of rebar	relatively flat ground, adequate counter-weight, water spray, protecting the operator
Water jetting	Partial removal of deterioratedconcrete slabs and bridge decks	1.4～4.3	Minimum labor, low noise, no dust, no vibration, and very accurate cutting, high production rate, remaining concrete surface irregular allowing good bonding to new concrete	Rebar shadow problems, costly, large quantities of water needed, dangerous due to the high pressures used, and disposal of the water that is mixed with debris, adequate protection operator

Hydraulic splitter	Full and partial structure and bridge removal	For splitter method, rate depends on hole pattern, hardness of concrete, and orientation of rebar	No vibration, inexpensive, little dust, remaining concrete undamaged, accurately control, dismantling precision, fair inexpensive-ness, high safety degree, fast speed, working continuously without interruption, high efficiency, and can be used underwater, small effect for surrounding environment, limited skills for requiring the operator	Time consuming and requires the use of breakers to expose rebar, splitter is usually employed as secondary means of separating and removing the concrete
Thermal lance	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, adequate protective measures for the workers
Explosive	Full and partial structure and bridge removal	Not applicable	Speed, short durations of noise and dust	Dust, noise, vibrations, flying debris, and dangerous

a) Demolition by hand

Demolition by hand is that the workers are equipped with air picks, jack hammer or pneumatic breaker to dismantle the concrete on a floor by floor downward sequence, and then the steel reinforcement is cut and removed with gas welding, which is the most widely used method and one of main types of demolition techniques.

The advantages of demolition by hand include the following:

- Manual removal of equipment is simple to operate, and the operation is strong mobility, and the concrete structures can be precisely removed.
- The maximum limit to reduce the impact of the demolition of the surrounding structure. It is effective in narrow and localised place, and efficient for simple structure.
- Old materials are well recycled.

However, some difficulties encountered with the demolition by hand are: due to manual operation, the efficiency of demolition by hand is low, and generally take the crowd tactics, so the requirements for engineering management are higher. Scaffolding is needed during demolition, and electric air compressor and other mechanical equipment are needed, which leads to high demolition cost. In the demolition, there is lots of noise and dust on site, and the impact on the surrounding environment is large. Therefore, before the demolition, the contractors need to do a good job with the surrounding residents coordination [11].

The usage or application areas for demolition by hand are to separate structure to be demolished from adjacent structures or from remaining adjoining, work near to live services or public area, where site or safety restrictions prevented mechanical demolitions, where the demolition has to be carefully controlled, site involving contamination, stripping out soft strip material such as door/window frames. For structural projections, such as balconies, canopies and verandahs extending beyond the building lines, demolition by hand held tools or the cut and lift process may be a safe solution[10].

b) Saw cutting

Saw cutting is suitable for alteration and additional works where accuracy in the cutting is important and the tolerance to noise and vibration is very limited. It can be used to cut concrete slabs and wall elements containing reinforcement into segments. and vary in thickness from several inches to several feet. In general, cutting methods are considered slow and costly for removal of large volumes of material from mass concrete structures. However, these may be secondary concerns when demolition criteria demand

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precision, reduced vibration, and reduced damage to the material that remains [12].Saw cutting generally includes conventional disc saw and chain saw, rotary-action diamond saws and wire saw.

Rotary-action diamond saws are the most common type of saw used to cut concrete. These saws produce straight precision cuts up to 21 in. deep in concrete by the high-speed grinding action of the saw blade. In the past, rotary-action diamond saws have been successfully used for building and highway demolition. In particular, these saws have been cost-effective for removal of free-standing walls. In general, the rotary-action diamond saw can be electrically or hydraulically powered or driven by a combustion engine. The blade is a thin rotary disc with diamond-tipped teeth along its outer perimeter. Lubricant is supplied to the blade through a hose connected to a lubricant storage container [13].

The advantages of rotary-action diamond saws include:

- Precision cuts can be made with minimal vibration and damage to concrete that remains.
- Relatively large sections can be removed at one time, and the surface of the cut concrete is smooth and relatively regular [2].
- Cooling water was used to cool the saw, so no dust is produced. Sawing produces negligible vibration and dust.
- A relatively safe operation can be maintained.
- The cutting equipment is light and easy to transport to the structure, and easy to operate.
- It will hardly affect the surrounding environment, completely meeting the requirements of green construction.

On the contrary, the disadvantages of saw cutting include: a. the cutting operation is slow and costly. b. Cutting depths are limited. c. The number of shapes that can be cut is limited. d. During the cutting operation, lubricant must be continuously applied to the blade to cool it and protect it from excessive wear. But cutting reinforced concrete increases blade wear and hence operation costs. e. Some additional safety requirements and procedures are necessary due to the high level of noise produced (see EM 385-1-1). f. It may be noisy and require equipment to supply and clean up the large quantity of water used to cool the saw. The cooling water will form dirty mud water [14]. g. Before a cutting operation begins, utility lines within the concrete in the vicinity of the cutting should be located and marked. h. The size and location of the reinforcement should also be determined before starting an operation. i. The cutting pattern should yield sections of satisfactory size to ensure safe handling for the equipment available for removal.

In one China case study, T1, T2 viaduct demolition project of Huanghua International Airport in Changsha applied saw cutting and BIM technology as the core of the new green cutting technology, which is faster than the traditional sawing cutting speed, greatly shorten the construction period; In the demolition process, there is no vibration, no pollution and no noise. The application of water collecting system in sawing cutting truly realizes zero discharge of polluted water and minimizes the adverse impact of demolition construction on Huanghua Airport and the surrounding environment. The application of BIM technology in demolition construction greatly reduces the difficulty of sawing cutting, and plays an active role in the design and implementation of sawing cutting. Engineering practice has proved that the new green sawing cutting technology studied, improved and optimized has effectively guided the demolition and construction of T1 and T2 viaducts in the transformation project of the liaison line of Huanghua International Airport of Changsha with good social and economic benefits.

c) Ball and crane

This is one of the oldest and most commonly used methods for building demolition. A crane uses a wrecking ball, typically weighing from 1,000 lb to 13,500 lb[2,15], which is either dropped onto or swung into the element to be demolished. Concrete members can be broken into small pieces, but secondary cutting of reinforcing may be necessary. Most importantly, the crane operator must be highly skilled to ensure maximum safety during the demolition operation.

The advantages of ball and crane demolition include:

- It is safety of project workers, because they are not required to be inside the collapse envelope of the structure during the demolition operation [16].
- It is simplicity of the operation.

On the other hand, the disadvantages of ball and crane include: It relates 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 [2]. Obviously, care must also be taken when operating around power lines. Additionally, the height of a building that can be demolished is limited by crane size and working room; however, buildings as high as 20 stories have been demolished [2]. What`s worse, demolition using a ball and crane can create large amounts of dust, noise, and vibrations [17]. To minimise the dust impact on the surrounding area, the structure to be demolished shall be pre-soaked with water before demolition. Water spraying shall continue on the structure during demolition [18].

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To ensure safe operation of a crane using a wrecking ball, the National Association of Demolition Contractors provides guidance for the safe operation of a crane using a wrecking ball. The ball weight should 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 to the load line with a swivel-type connection to prevent twisting of the load line. Taglines may help control the ball during the swinging operation. Smoothness in controlling the swing of the ball is important.

This method is suitable for dilapidated buildings, silos and other industrial facilities. However, the operation requires substantial clear space. The application also demands high level skill operators and well-maintained equipment. The safety hazards of cranes operating near electrical wires are well known. The absolute limit of approach for a crane boom near a power line is 10 feet. A signalman must be assigned to warn the operator when he is nearing the limit of approach [19].

d) Hydraulic excavator

Hydraulic excavator, with specialist attachments such as crushing hammer, pusher arm, wire rope and clam shell, is used for almost every conceivable demolition work from dismantling the roof to breaking up and removing the foundations, replacing the once dominant crawler cranes and demolition balls. However, its use on demolition projects is not straightforward in practice due to complicated site conditions and other constraints. The concerns and good practices of the mechanical demolition generally included the following: (1) These methods shall only be applied to isolated buildings on relatively flat ground. It shall also have adequate counter-weight to prevent overturning during the operation; (2) The equipment and accessories such as attachments and rope shall be inspected frequently and shall be repaired or replaced whenever necessary; (3) Sufficient water spray or other anti-dust precautions shall be provided to minimise air pollution by dust; (4) The cab of the machine shall be equipped with impact proofed glass and its construction shall be robust enough to protect the operator from flying debris[20].

The demolition method of hydraulic excavator has many advantages:

- Flexibility, convenient use, good maneuverability, strong adaptability, and the ability to strip or cut steel reinforcement.
- It can be used to break up all kinds of concrete structures and rocks and get good economic benefits [21].
- It is suitable for densely populated or built-up areas, and the structure is the small and medium-sized building structure under the height of 15m to dismantle.
- It is also suitable for the construction period is not tight.
- In many cases, the comprehensive demolition cost of excavator demolition method is lower than that of blasting demolition.

Nevertheless, the main disadvantages of the demolition method of hydraulic excavator are noise, dust and vibration, low efficiency, long construction period, many unsafe hidden dangers, relatively poor comprehensive benefits. In addition, it may be restricted in areas of limited work space [22].

At present, the most significant technological progress of crushing hammer is intelligent crushing hammer. It can automatically monitor and adjust its output shock energy and shock frequency characteristics according to the crushed objects. When a solid structure (hard)is broken, the single impact energy is automatically increased and the impact frequency is reduced to make it more capable of breaking; When the non-solid structure (soft) is broken, crushing hammer can automatically accelerate the impact frequency, reduce the single impact energy, so that the crushing hammer has higher production efficiency. And when the structure is broken, it will reduce or stop output, in order to protect the hammer, extend its service life.

e) Water jetting

Water jetting involves the use of a water jet stream pumped at high pressure to erode the cement matrix and wash out the aggregates. Moreover, BS 6 187:2000 defined high-pressure water jetting as "all water jetting processes including those using additives and abrasives where there is energy input to increase the pressure of water. In demolition the process is used, e.g. for cutting out concrete from around steel reinforcing bars where the latter are to remain". For example, a high-pressure water jet about 250-300 MPa from a nozzle about 0.3-0.5 mm in diameter can cut through plain concrete by abrasion [6].Its usage or application areas are: where hot cutting or work is not allowed e.g. chemical plant, where need to cold cut steel in areas such as refineries, where vibration must be avoided, with contaminated equipment or explosive atmospheres, vessels previously containing flammable or toxic material (radioactive). Reference should be made accordance with the Water Jetting Associati on Code of Practice [23].

The advantages of water jetting include:

- It is minimum labor, low noise, no dust, high production rate, no vibration, minimising dust and fire hazards,
- Remaining concrete surface irregular allows good bonding to new concrete [3].

However, the disadvantages are rebar shadow problems, it is costly, needs large quantities of water, and disposal of the water that is mixed with debris. In addition, large fragments of aggregate and other debris are sometimes dislodged and ejected from the cut with considerable force. This hazard requires the operator to wear adequate protection and the cutting area to be kept clear of other personnel [12].

The productivity of the water jet has greatly improved over the last decade, and it is now becoming competitive with some of the other removal devices. Improvements that are under development should make the water jet even more competitive. The water jet has the potential for being a primary means for removal when it is desired to preserve the reinforcement within the removal area for reuse. However, at present, the water jet, like other cutting devices, may be better used in support of primary removal methods [24].

Demolition by high pressure water jetting was used in bridges, independent chimney, basement and retaining wall, masonry and brick arches, vessels and tunnels. The research results also indicated that the water jetting was used in practice and the combinations of different techniques are usually employed.

f) Hydraulic splitter

Due to the low tensile strength of concrete, hydraulic splitter [25] can easily dismantle large sections of concrete structures. Holes ranging from 1 to 2 inches in diameter are drilled into the concrete. The wedge of splitter is inserted into the hole and the subsequent hydraulic pressure forces the concrete to split. Controlling the crack direction and the movement of the demolished mass may be difficult using hydraulic splitter. Additionally, when reinforced concrete is being split, it is almost always necessary to utilize a hydraulic or pneumatic breaker, either hand-held or machine-mounted to expose the reinforcing bars for cutting.

Hydraulic splitter has many advantages:

- It is accurately control, dismantling precision, fair inexpensiveness, high safety degree, fast speed, working continuously without interruption, high efficiency.
- The surrounding environment will not be impacted, especially it can be used closing to the precision equipment, and they can be used underwater.
- It is quiet and does not cause vibration, fly rock, or dust other than that yielded by drilling and secondary breaking operations. This can be overcome by coring the holes with a diamond-tipped coring machine, but at far greater cost [2].
- The splitter is best suited for shallow holes at any angle. It can be used on wall surfaces and in areas of limited work space.
- Limited skills are required by the operator.

However, its disadvantages include: for removal of surfaces from mass concrete structures, control of crack plane depth is somewhat limited. It requires the use of breakers to expose reinforcement for cutting. Secondary means of breakage are often required to separate and break sections to increase efficiency in handling and removal work. It is a time consuming process, so the concrete splitter is usually employed as secondary means of separating and removing the concrete, which adds to the cost of removal.

Hydraulic splitters have been used at Corps projects such as Hiram M. Chittenden Lock, Seattle District, in the removal of an existing fish ladder structure and Markland Dam, Louisville District, in the removal of pairs of reinforced blocks atop downstream pier stems. Splitters have been used on a variety of other types of structures such as bridges, nuclear reactors, retaining walls, and concrete bank vault walls. They are most suitable for large volume plain concrete demolition and rock excavation cooperated with crusher [26].

g) Thermal lance

Thermal lance means a high temperature torch with heat source generated from fusion of oxygen and metal to melt concrete and rebars [27]. And specifically, the heat is generated using flame, plasma, or laser beam. In the flame process, 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 using acetylene gas to obtain a high temperature of 2,000 - 4,000°C, which are applied to the concrete [3]. The cutting speed of the thermal lance is 200~400 mm/min. The cutting speed of silica aggregate is generally faster than that of limestone aggregate. Because of the steel bar reacts with oxygen to produce high temperature, so steel plate and steel bar cutting faster than concrete. In addition, cutting speed also depends on the smoothness of discharge of the molten slag.

The advantages of this method include:

- It is no vibration, a low noise level, it can be used underwater.
- 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, and it's easy to control with a robot.
- Thermal lance may be used like the diamond saw to improve crack control and reduce over breaking [12].
- It is especially practical and effective for cutting reinforced concrete.
- Thermal lance can be used to remove surfaces from mass concrete structures.
- Protective concrete structures from nuclear reactors can be dismantled with thermal lance, but radioactive smoke has to be collected by cutting decommissioned nuclear reactor equipment.

The disadvantages of thermal lance are that it is slow and 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. Thus, the use of a thermal lance in cutting reinforced concrete shall not be used unless: (a) The project demonstrated that there is no other viable alternative; (b) Adequate protective measures are provided to isolate the operation and to prevent any potential fire spreading out; and (c) Adequate protective measures are provided to prevent the injury of the workers, and any third party by flame and the molten concrete.

h) Explosives

By detonating explosives, blasting methods employ rapidly expanding gases confined within a series of boreholes to destroy the building support structure and produce controlled fractures which provide for easy concrete removal. In general, blasting methods are most cost-effective and expedient means of removing large volumes of distressed or deteriorated concrete [28]. But, due to dangers inherent in handling and usage, blasting is considered most dangerous and requires more stringent controls than any other methods of demolition. For the demolition of concrete structures, it is usual to drill holes at a predetermined angle into the concrete to be removed. The holes are then charged with an explosive which is electrically detonated. Empirical judgment based on the skill and experience of the operator is the basis for blasting design. Recent advances in blasting design include the utilization of recognized formulas and calculations which determine the position, angle and depth of the borehole, as well as the size of the charge. A simpler but far less effective method of blasting is to lay the explosive charge on the element to be demolished and cover it with sandbags. Another method, particularly useful for containers, is to fill the structure with water and detonate an explosive charge which has been suspended at the center. The water transmits shock waves to the surrounding walls. Shaped charges for the directional cutting of elements are also available.

The explosive method has many good characteristics:

- It is high speed and efficiency, and low comprehensive cost.
- Before blasting period, it does not account for the construction period. And after the completion of blasting, the wastes can be cleaned up, so it does not affect the next process of structure construction, and cleaning other parts does not occupy the main progress.
- The benefits of demolition by blasting are low labor intensity, short construction period.
- It can avoid to bring disturbance for the surrounding people due to long-term construction.

However, the explosive method will produce some negative effects due to blasting: the strong shock wave will cause great safety hazards to the surrounding environment, which produces vibration, blasting flying stone, dust, etc. The contractors need to be strict technical measures to avoid the surrounding environment being affected. Due to the rapid development of blasting technology, the technical parameters of blasting are restricted and supplemented by other auxiliary measures, such as setting up protective shed and covering. Thus, the method of covering protective blanket can reduce dust, vibration and noise caused by blasting. detonation. The rational improvement and utilization of blasting technology is very helpful to the development of concrete structure demolition technology [11].

In summary, explosives are versatile and have great flexibility in terms of work output. Nevertheless, excessive ground vibration may damage adjacent structures and air blast may cause superficial damage such as window breakage elsewhere. The National Association of Demolition Contractors states that the use of explosives to demolish entire buildings or portions shall not be permitted unless there is sufficient clear space in all directions equal to 75% of the height of the building being demolished. Precautions should be taken to stop flying debris and in all circumstances strict site control must be maintained to ensure the safety of workers and the general public [2].

The rapid development of explosive technology makes it widely used in engineering construction applications. At present, the commonly used explosive demolition method is mainly shallow hole differential blasting technology: drilling holes according to the design hole mesh size on the support beam, loading explosives and millisecond lightning tube, method of removing the supporting beam after initiation.

Successful blasting case studies-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 [29]. Another case is that explosives were used on the Sunshine Skyway Bridge (Tampa Bay, Fla.) demolition project, which called for the removal of 61,200 m3 (80,000 cu yd) of concrete and 6,182,000kg (6,800 tons) of structural steel [30]. 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 [3].

V. Green Demolition Technologies

At present, most of the demolition projects undertaken are complex in nature demanding greater skill, experience and precision than ever before. In addition, more legislation that is stringent and growing commercial and environmental pressure have made a major impact on the selection of demolition techniques. Furthermore, various types of new demolition techniques are available in the demolition industry, which make the selection more complex.

In addition, urban residence construction is in the stage of rapid development, so the number of high-rise and super-high-rise buildings in the city shows a high-speed growth trend. The traditional demolition technologies have many problems such as loud noise, dust pollution and obvious vibration, which often bring many bad effects to the surrounding environment. It is contradictory with the requirement of green environmental protection, especially in the prosperous areas of some cities. Therefore, green demolition technologies of reinforced concrete structures have been widely used and developed. The novel eco-friendly green demolition technologies are as follows:

- Electric heating method
- Chemical expansive agent
- High-voltage pulse technology
- Resonance demolition method
- Cut & down construction method
- Drilled core demolition technology
- Intelligent robot demolition technology

Green demolition technologies improve the demolition safety and prevent the pollution. Table 2 provides a summary description of green demolition technologies [3, 31-33].

Table 2: Summary of Green Demolition Technologies of Concrete Structures

Method	Applications	Production (m^3/h)	Advantages	Disadvantages
Electric heating method	Demolition of reinforced concretestructures.removal the concrete protective shell of nuclear reactor	0.12~0.14	Easy to control and recycle, easier to set coils on the concrete surface, no noise, no vibration,no dust, no explosive, lower hazards to workers, safety and environmental protection	Peeling down the concrete cover, expensive; the heating coil needs to be cooled, high- power equipment
Chemical expansive agent	Full and partial bridge removal, a restrictive environment where noise, flying debris and vibration are less tolerated, foundation works, pile caps or structures	For this method, rate depends on hole pattern, hardness of concrete, and orientation of rebar	No vibration, no noise, safety, and nonexplosive, easy to complete	Costly, more time, specialized and well-protectedworkers, cutting the reinforcement
High-voltage pulse technology	Demolition of reinforced concrete structures in town populated environment	Rate depends on voltage pattern, hardness of concrete, electrolyte or fuse type	No flying stones, no dust, no noise, and no toxic or harmful substances, efficient and controllable. effective, directionality, high energy utilization efficiency	Expensive, high working voltage, bulky generator, unfavorable handling, serious ablating electrode, insufficient

				attention to safety and insulation problems, holes being drilled to insert electrodes
Resonance demolition method	This method is still in the experimental stage of development, removal a small number of non-load-bearing or a small number of load-bearing structure	Rate depends on frequency, the responses (displacement, stress, etc.) of forced vibration	No dust, no noise, economical, green and safe, high energy utilization efficiency, easy to recycle resources	Dismantling in blocks, and the erecting of the resonator being more troublesome
Cut & down constructio n method	Dismantling concrete structures	0.03	Enclosed construction environment,efficie ncy, more eco-friendly, no dust, no noise and no vibration, no damage to the surrounding buildings, no waste thrown down from height, no need to move the personnel and waste up and down, and the security is higher, CO_2 emission is reducted, materials are classificated to recycle, the decoration materials recovery rate is up to 93%	Large tonnage multi-point hydraulic synchronous jacks being needed, experienced operator
Drilled core demolition technology	Removal the elements of reinforced concrete structure with relatively dense steel bars, demolition of reinforced concrete support elements	Rate depends on drill type, drill diameter and length	Simple working procedure, easy access to use machinery and low cost. high construction accuracy, high speed and no dust pollution, the concrete surface is smooth, no need for other fixed devices	Low efficiency, more time

Intelligent robot demolition technology	In the situation of hazardous or potentially dangerous situations arise, pre-weakening of structures for demolition by explosives, unstable structures, Nuclear contamination	—	It can engage in high-riskdemolition operations and reduce casualties, it can greatly improve the efficiency of demolition and reduce dust pollution caused by demolition, minimum labor results in reduced cost, more energy efficient, more reliable, it is suitable for places with limited space	—

a) *Electric Heating Method*

To address the problems of disturbing people and environmental impacts during demolition, Japanese researchers have carried out a series of experiments with the electric heating methods. There are two categories of electric heating methods: (1) direct heating method; (2) induction heating method.

Direct heating method has become the development focus of green demolition technology. The two ends of the reinforcement are exposed in direct heating method and electrodes are installed. Low voltage (25V) and high alternating current are directly applied to generate resistance loss of heat, resulting in the expansion of steel reinforcement. The thermal expansion of steel reinforcement and surrounding concrete produces tensile stress in concrete, and a continuous crack in the heated steel bars breaks the bond between the steel bars and the concrete. Then concrete around the crack can be easily knocked off by using a chisel or hydraulic hammer. Ultimately, concrete cover can be removed by cracking and delamination occurs by electrically heating the reinforcing steel[15]. Heating steel bars is beneficial to peel off the concrete cover. The rebar can be heated to 400~500℃.This temperature value is usually achieved in 7~8min. The frequency of the heater used is 400 Hz and the maximum voltage is 25 V or 50 V. The current is 2,300 A or 1,150 A.

The advantages of direct heating method are as follows:

- This method uses electric energy, so it is easy to control.
- The noise and vibration are negligible during removing the concrete cover.
- The concrete and steel are chipped away in blocks, so the dust produced is minimal.
- The hazards to construction workers and the environment are reduced because of no explosives.
- It is a new safety and environmental protection method for the demolition of reinforced concrete structures.

Because of the above advantages, this method has been used for drilling underground diaphragm wall. Moreover, this method applied to remove the concrete protective shell of nuclear reactor works well. However, the drawback of direct heating method is that the electrodes need to be attached to the steel, so the concrete cover is cut open to expose the two ends of the steel for heating.

Induction heating method uses an induction coil to expose the steel bars buried in concrete to an alternating magnetic field, and generates stray currents in the steel bars. The resulting loss of resistance is used to heat the steel reinforcement and crack the concrete. The method was tested by Japanese researchers in 1978, using C-shaped magnets. The researchers created an alternating magnetic field using an eddy current flat coil. The frequency is 3 Hz, 32 Hz and 200 kHz, and the power is 100 kW and 200 kW, which is used to heat a specimen with concrete cover of 100 mm and steel reinforcement diameter of less than 35 mm or 38 mm. At 200 kW, the temperature increase is much larger than at 100 kW. The test results show that no significant difference between the frequencies of 3 Hz, 32 Hz and 200 kHz [33].

This method has the same advantages as the direct heating method, and it is easier to set coils on the concrete surface. However, the following problems need to be solved: (1) Induction heaters are expensive; (2) An appropriate method must be developed to cool the heating coil; (3) Heating steel reinforcement with a thick concrete cover requires high-power equipment.

b) Chemical expansive agent

Chemical expansive agents undergo a large increase in volume when properly mixed [34-37].These agents are placed in holes drilled in concrete in a predetermined pattern. Once the expansions of the mixture by hydration cause the splitting of the concrete and a fracture (BS 6 187, 2000) [6]. The chemical composition of these agents consists of calcium oxide that expands when hydrated [3]. Chemical expansive agent is a suitable application in a restrictive environment where noise, flying debris and vibration are less tolerated. A drilling pattern shall first be designed. For large projects, test breaking shall be performed. Secondary efforts are required to further break down and remove the debris by mechanical means.

The advantages of chemical expansive agents include:

- They are nonexplosive, so no vibration, noise, fly rock, or dust is produced other than that produced by drilling and secondary removal methods.
- Reasonably safe operation can be maintained.
- It can be used to presplit large sections of concrete for removal.
- It can be used to propagate vertical crack planes of significant depth for controlled presplit ting within a mass concrete structure.
- Limited skills are required by field personnel.

The disadvantages of chemical expansive agents include: The overall operation is somewhat costly when drilling and secondary removal expenses are included, and it takes more time to complete a demolition job with chemical expansive agents than with hydraulic splitters or explosives. Demolition by chemical expansive agents is highly specialized activity and must be undertaken only by, or under supervision of trained personnel. Control of crack plane depth is somewhat limited. As the agent will irritate the skin and eyes, the rubber gloves and goggles are worn to protect the worker. Secondary means are required to complete separation and removal of the concrete section from the structure. For reinforced concrete, a means of cutting the reinforcement must be employed. A couple of days may be required before presplitting becomes optimum. Any large voids in a borehole are usually not detected until an excessive amount of agent has been used.

In addition, the chemical agent is formulated to be used at a certain temperature, and any deviation from this temperature will reduce the expected expansive pressure. Freezing the chemical agent will greatly reduce its effectiveness [2]. Chemical expansive agent may be used on foundation works, pile caps or structures that are fully supported [10].

c) High-voltage Pulse Technology

High-voltage pulse technology has been identified as one of the fragmentation mechanisms with minimal environmental impacts [38–42]. This method uses a pair of electrodes placed in the concrete and take advantage of liquid-electric effect or fuse explosion to produce mechanical action, and when high frequencies and pressures are applied, the temperature of the liquid or fuse sandwiched between the electrodes rises, and the thermal stress causes the concrete to crush into many small pieces. A report from the UK shows that a 100mm concrete cube can be peeled off by applying a pulse discharge of 5~80μs.

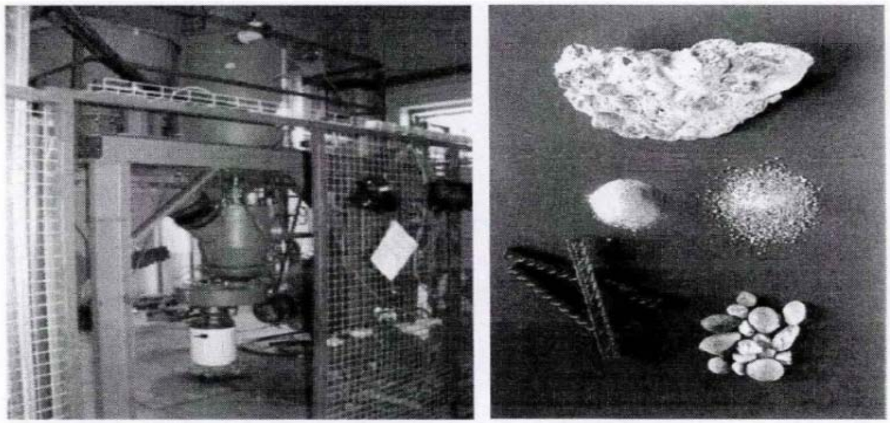
Compared with other demolition technologies, high-voltage pulse technology has the following advantages:

- It achieves the purpose of the separation of steel bars and concrete. Meanwhile, this method does not produce flying stones, dust, noise, and either generate toxic or harmful substances.
- It provide effective means for demolition of reinforced concrete structures in town populated environment.
- The demolition process can be controlled by regulating the discharge energy, and it is easily controllable.
- Using high pressure pulse to dismantle concrete has directionality, which can effectively use resources and improve energy utilization efficiency.
- It can crack or break the concrete in some occasions where the conventional demolition methods cannot be realized.

But the high-voltage pulse technology is also pointed out some problems: It uses expensive equipment, high working voltage, bulky generator, and it is unfavorable handling. The electrodes are serious ablated, and the safety and insulation problems of of the equipment do not get adequate attention, which have limited the popularization and application of this technology. Besides, Holes need to be drilled to insert electrodes. The analysis results show that the working voltage should be reduced reasonably, and the safety and insulation of the equipment should be improved. It is advantageous to miniaturize the device and enhance its portability with a small single discharge energy, and to improve the discharge frequency and prolong the service life of the electrode. Which should be urgent problems to be solved in the future.

In order to facilitate the recycling and utilization of resources, Bluhm et al [43,44] from Karlsruhe Research Center developed a semi-industrial prototype for dismantling concrete materials. The pulse power supply of this prototype is Marx generator. The working voltage is 350 kV and the working frequency is 10 Hz.

The processing capacity of the prototype is 1000kg/h. Concrete blocks can be recycled after being broken [45] as shown in Figure 1.



(a)Semi-industrial prototype (b)Concrete crushing effect

Figure 1: Semi-industrial prototype and crushing effect drawing for dismantling concrete [45]

d) Resonance Demolition Method

Institute of Earthquake Prevention and Disaster Reduction of Lanzhou University in China uses the resonance demolition method [46] to dismantle concrete structures. Firstly, a resonator is installed in the wall removed to measure its natural vibration frequency, and then the resonator is used to make wall vibration. When the frequency of loading achieves consistently with that of the wall, the wall is broken and fell off because of the resonance.

The resonance demolition method has great advantages over the traditional demolition methods:

- It does not produce dust or noise, because the natural vibration frequency of the wall is not within the range that can be distinguished by human ears;
- It is economical, green and safe, and it can make full use of the energy released by the resonator, that is, the energy utilization efficiency reaches the highest [3].
- This method can reduce the impact of harmful gases on the environment.
- The resonance demolition method is conducive to the recovery of some resources, which is up to the requirements of sustainable development strategy.

Up to now, this method is still in the experimental stage of development. The failure problems of uncertain vibration structure systems have followed two paths. One is failure research on the basis of the responses (displacement, stress, etc.) of forced vibration. The other is failure research on the basis of the relation between natural frequency and forcing frequency of vibration systems at resonance and non resonance [47]. Which needs a lot of improvement. Furthermore, if the resonance demolition method is used to dismantle the wall, the wall can only be dismantled in blocks, and the erecting of the resonator is more troublesome. Reinforced concrete column and beam cannot be removed by resonance demolition method, which can only remove a small number of non-load-bearing or load-bearing structure. Thus, there are many limitations in using resonance demolition method.

e) Cut & down construction method

Cut & down construction method is also known as Kashima construction method, which is an advanced and sustainable way of demolishing high-rise buildings. Its basic idea is to dismantle concrete structure from the bottom of the building to its top. Firstly, scaffolding and sound insulation panels are built around the first floor of the building, and the other components are removed except for load-bearing columns of the first floor. And then some large-tonnage jacks are used to replace the columns of the first floor. The above operation is repeated again and again, and the concrete structures are dismantled by lowering the storey to remove it.

The cut & down construction method has many advantages:

- It can be operated in enclosed construction environment, so it is very good to avoid the generation of dust and reduce the construction noise and vibration.
- There is no damage to the surrounding buildings.
- There will not be the phenomenon that waste is thrown down from height, because construction is operated on the ground.
- The security is higher, Because it is different with other methods to dismantle concrete structure from the top of building. The ground floor of the building is used to establish a construction area, so the

demolition of the high-rise building just needs to be completed on the ground. And there is no need to move the personnel up and down,

- The construction progress is more eco-friendly [2], and the construction period can be shortened, because demolition operations near the ground are efficient.
- CO2 emission is reducted, because more than half of CO2 emissions come from the fuel used by machines in the demolition process, and this method can improve the construction efficiency and reduce 8.5%CO2 emissions.
- The decoration materials recovery rate is up to 93%.Because this method is used to dismantle concrete structures floor by floor, and decoration is deconstructed and materials are classificated to recycle.

Obviously, in the demolition of high-rise and super-high-rise buildings, this method has advantages in environmental protection and shorter construction period. In contrast, the conventional demolition method uses a tower crane to lift heavy machinery that is used to cut columns and beams up to the roof, and then starts from the top floor and dismantles them from top to bottom. Scaffolding must be erected around the perimeter of the building and measures must be taken to prevent noise and dust from intruding on the surrounding area. But the cut & down construction method is only carried out near the ground, which is easy to conduct sound insulation around the building. Because this method does not make a lot of noise, it is especially effective in areas with lots of super high-rise buildings nearby. However, the cut & down construction method has some disadvantages: (1) It needs large tonnage multi-point hydraulic synchronous jacks; (2) The operator must have proven experience and skill for operating the jacks [48].

A case study is the Prince Hotel of Akasaka in Japan with 138.9m height, which was once an iconic building in Tokyo. The hotel was removed from the bottom and supported the floor by jack in 2012. Every two floors was a unit, and the building was dismantled from low to high floor by floor. After half a year, the building was finally silent razed to the ground. Since most of the work was done inside the building, there was no sign of construction outside, but only the building was saw to sank into the ground floor by floor. It can significantly reduce dust and noise, and there was no damage the building around the hotel. In addition, two office buildings with 57.9m and 69.1m height and the 108m high Resona Maruha building were dismantled by cut & down construction method. According to calculation, it would take 9 months to demolish Resona Maruha building by using the traditional construction method, while it only took 6.5 months to complete the construction by using the cutting construction method, including the construction of the core wall, Which can be shortened by 2.5 months.

f) Drilled core demolition technology

Drilled core demolition technology is appropriate for the elements of reinforced concrete structure with relatively dense steel bars. The coring drill can avoid tension bars and stirrup bars, and drill the support elements vertically or horizontally through the gap between the rebars. After the drilling is completed, the main bars will be cut off with a cutting machine, and finally the sections after cutting will be lifted by a crane [11].

This method has some advantages:

- It combines the characteristics of high safety of manual demolition of concrete support and fast mechanical crushing of concrete support.
- It can simultaneous operate by several coring drill and greatly save the construction period.
- It has simple working procedure, easy access to use machinery and low cost.
- This method has high construction accuracy, high speed and no dust pollution. The concrete surface is smooth, and it is mainly applicable to the demolition of reinforced concrete support elements.
- Vacuum disc drill can firmly adsorb on the flat building, no need for other fixed devices, so the building surface is not damaged at all.

However, the drilled core method has some shortcomings: (1) The construction efficiency of this method is still relatively low. (2) The frame set up will take up a large amount of construction time.

A case study is that an inter-city railway project. It is all underground engineering, and 2 ~ 4 internal supports are set vertically in the foundation pit. Among which the first one is reinforced concrete internal supports, and the rest are steel tube supports. There are 750 reinforced concrete supports need to be removed. In the demolition site, a type 100A or 160A drill (5 ~ 10cm in diameter and 80cm in length) is used to drill vertical and horizontal holes in the gap between tensile and stirring bars for the support beam. After drilling, a cutting machine is used to remove the main bars. Then the cutting work is finished. Finally, the supports are lifted away by gantry crane from the foundation pit. The foundation pit is safe and reliable. The concrete support beam can be lifted away from the foundation pit, which greatly improves the work efficiency and saves the time limit [49].

g) Intelligent robot demolition technology

Intelligent robot is mainly used in manufacturing industry at the beginning. With the continuous maturity of robot technology, it is gradually applied in mechanical

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demolition of construction industry. In the situation of hazardous or potentially dangerous situations, consideration should be given to the use of remotely controlled machines and robotic devices. The operator can be removed from the dangers of working in a confined or hazardous area. The machines can be controlled by digital signalling system transmitted via cable or radio.

The advantages of intelligent demolition robot over general mechanical demolition are:

- It can engage in high-risk demolition operations and reduce casualties.
- It can greatly improve the efficiency of demolition and reduce dust pollution caused by demolition.
- Minimum labor results in reduced cost, more energy efficient, more reliable [50].
- It is suitable for places with limited space

Foreign manufacturers of dismantling robots mainly include BROKK company of Sweden, TOPTEC company of Germany and F1NMAC company of Finland [51]. After continuous improvement and development, the demolition robot developed by Sweden BROKK company is in the international leading position in various technologies. It is the largest supplier of demolition robot at present, and its products are sold all over the world. For example, one of the robots that used remote demolition technology is the ISO Model from BROKK. This robot is designed for using in the regeneration and renewal of urban, commercial and industrial environments. It also had been designed to better suit accessories, particularly heavier tools up to 230kg and either a 15kW or 18.5kW electric motor to drive the machines. Its standard weight exclude accessories are 1,900kg with a basic work area radius of 4550mm, which can be increased depending on attachments [52].In addition, intelligent robot can be combined with water jetting, thermal lance and other dangerous demolition methods.

A case study is a high-velocity, high-pressure water nozzle of hydro demolition equipment, which was housed in a robot that moved across a concrete slab in the U.S. in the mid-1980s. The nozzle(s) moved back and forth on a transverse track allowing for a full width movement of about 6 ft[53]. The microprocessor-controlled hydro- demolisher from FIP Industriale can be programmed to cut to any depth, removing as little or as much concrete as needed. The hydro demolisher removes varying amounts of concrete by adjusting how quickly the nozzle moves and how fast the mobile unit moves forward [54, 55]. The Conjet concrete removal system from Atlas Copco also consists of a high-pressure nozzle (117,215 kN/m2 or 17,000 psi) housed in a tire-mounted, microprocessor controlled robot.

The usage or application areas for demolition robot are: (1) Dangerous environments for operations e.g. unsafe structures or danger to personnel; (2) Internal demolition e.g. Concrete floors in muilistorey structure; (3) Pre-weakening of structures for demolition by explosives; (4) Confined areas and where there is danger of collapse or unstable structures; (5) Nuclear waste-contaminated environments.

VI. Safety issues in Concrete Structure Demolition

Whatever the demolition method or the size of the job is chosen, safety issues, including protecting workers and the public, protecting adjacent structures, and protecting existing utilities, are most important factors needing to be taken into account.

a) *Protecting workers and public*

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

- Develop proper demolition plans including detailed engineering calculations showing load determinations and structural analyses. Which should also show the demolition sequence, staging, services, transport route and access, equipment location, restraints and false work for structural stability, and hazard materials.
- Develop a comprehensive "Code of Safe Practice" that includes a plan for the use of personal protective equipment (including hard hats, gloves, goggles, construction boots, tie-off, protective clothing, seat belts and canopies).
- Remove hazard materials such as asbestos and polychlorinated biphenyls (PCBs) must be done in accordance with regulations set by the Occupational Safety and Health Act (OSHA) and the Environmental Protection Agency (EPA) to ensure the workers will not be harmed by these extremely dangerous materials.
- Develop a maintenance plan for keeping all pieces of equipment on the job in good working condition for the duration of the project, and rehearse the demolition process to ensure tools are safe and effective.
- Develop a dust control plan (such as using water sprays).
- Develop a plan to prevent debris from injuring the workers and public (such as using debris nets), or sort and process the recyclable materials on site.
- Develop a plan to protect the public from noise (such as monitoring work-hour schedules and noise levels), or use green demolition technology.

b) *Protecting public facilities*

Underground and overhead, two types of public facilities may exist in the vicinity of a demolition project. Underground utilities may include gas mains, sewer lines, and water pipes. Overhead utilities may include the electric lines, power and telephone lines.

To protect underground facilities, some of the measures can be taken:

- High-pressure water lines should be shut down within the demolition zone.
- Locate and mark warning signs within the gas mains and sewer lines zone.
- Steel plates may also be used as covers to protect against impact.
- Debris piles should be built on top of such lines to provide a cushion against impact from falling objects.
- No large demolition waste should be allowed to drop.

To protect overhead facilities, the contractor should request government approval and 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.

c) Protecting Adjacent Structures

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

- All possible loads on concrete structure should be analyzed to establish a safe loading range before demolition starts and to ensure that floor slabs do not become overloaded by debris and/or heavy pieces of equipment.
- All load-bearing beams and columns at a lower level should not be cut or removed until demolition at the upper level is completed. Caution should be exercised in removing when they tie into party walls. Beams and columns should always be well secured with wire rope or chains when they are cut.
- 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.

VII. Summary and Conclusions

Concrete structure demolition is a complicated process that needs careful planning and management. More emphasis should be placed on selecting rational demolition methods and equipment to achieve a satisfactory outcome. A number of traditional and green demolition methods were described in the paper, providing a comprehensive literature review of how each method works and what type of projects it serves. Advantages and disadvantages of each method were contrasted. This paper then discussed safety issues for protecting workers and public in concrete structure demolition, and how a demolition engineering should be considered to provide a safe work environment.

By comparison, it is proved that green demolition methods have many irreplaceable advantages over traditional demolition methods: easy to control and recycle, no noise, no vibration, no dust, no explosive, lower hazards to workers, safety and environmental protection. Concrete structure demolition is becoming an increasingly important subject when dealing with building and transportation infrastructure rehabilitation and maintenance as more and more structures and bridges reach their design service life and become candidates for replacement, rehabilitation, and/or widening. It is the general trend to optimize the selection of suitable demolition technology and to develop innovative green and safe demolition technologies.

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