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# Japanese Efforts to Promote Steel Reuse in Building Construction

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## Abstract:

This paper describes the state-of-the-art of structural steel reuse in Japan. A significant part of the material is taken from a document titled the AIJ *Recommendations for Sustainable Steel Building Construction (Draft)* available only in the Japanese language. The motivations and potential benefits of steel reuse are examined. The affinity between seismic design requirements and steel reuse is highlighted through a concept known as "damage-control" design. Some technologies for disassembly are introduced. The historical development and changes in Japanese structural steel is summarized, followed by a discussion on reusability of historical steel reclaimed from existing buildings. Reuse projects whose details are known to the authors are listed. The heart of the paper is a design procedure that specifies the structural

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engineer’s role and involvement in planning, material procurement and executing a steel reuse project. The discussion is concluded by six directions that should be pursued to make steel reuse a wide-accepted reality in Japan. Among those directions are research needs to establish a procedure to quantify the remaining structural performance of reclaimed steel considering possible exposure to earthquakes, establish connections that allow for easy disassembly, and introduce modularized structural systems. High seismicity and the general practice to adopt full moment frames pose unique challenges for steel reuse in Japan.

**Subject Headings:** Steel reuse; Environmental impacts; Seismic design; Damage-control design; Steel property; Traceability.

# Introduction

The purpose of this paper is to describe the key information and discussions in the AIJ *Recommendations for Sustainable Steel Building Construction (Draft)* (AIJ 2015), hereinafter referred to as the *Draft Recommendations*, which summarizes the state-of-the-art of structural steel reuse in Japan. Supplemental information, particularly on structural steel and building design in Japan, that is not included in the *Draft Recommendations* (AIJ 2015), is provided to aid readers who are not familiar with Japanese steel construction.

Japan is among 19 countries that pledge to reduce greenhouse-gas emissions to net zero by 2050. Without doubt, innovations to replace fossil fuel with hydrogen and to implement carbon capture, utilization and storage are essential to meet the ambitious goal. Nevertheless, action of the building industry, which covers residences, office buildings, and industrial facilities, is vital. According to statistics, the building industry is responsible for one third of domestic carbon dioxide emission, one third of which is embodied and two thirds is operational (AIJ 2013a). More than a decade ago, the Architectural Institute of Japan (AIJ 2009; AIJ 2020) set principles to change the mindset of our industry: 1) Buildings shall be designed for extended longevity; 2) An integrated life-cycle management scheme from design, construction, usage, repair and renovation to disposal shall be implemented; and 3) Eco-friendly material shall be promoted. Steel reuse is emerging as a key approach by which the structural steel community can act on these principles, and thereby, contribute to sustainable development of our society.

Fig. 1 explains steel reuse in a circulation diagram. Circulation of structural steel may be separated by the manufacturing processes and destination after the end of life of the structure. Structural steel in Japan is produced by the blast furnace or electric furnace process. Although there is no mandate to do so, many engineers specify blast-furnace steel for primary load-carrying members. Circulation in the construction industry includes fabrication, erection, repair and maintenance during use, and end of life. At the end of life of the building, the steel may be reused, recycled to produce newly manufactured steel, or disposed. In Japan, nearly all steel is recycled. Reuse, which is the most ideal option to serve sustainable development, is prevented by a number of barriers. The barriers described in the literature (e.g., Addis 2006; Dunant et al. 2017; Tingley et al. 2017; Hopkinson et al. 2019), such as lack of interest, confidence in the retrieved steel, supply, integrated guidance, among other factors apply to Japan.

As discussed by Addis (2006), reuse of construction material is not a new concept. In fact, historically, in most if not all parts of the world, it was common to reuse structural and nonstructural materials, be it brick, timber, glass, or steel. Reuse became increasingly rare as the availability of newly produced material increased in both quantity and cost. However, over the last decades, across the globe, reuse is given renewed attention in the light of sustainable development and energy conservation, driven by increasingly stringent regulations on waste and recycling, and greenhouse-gas emissions (e.g., Gorgolewski et al. 2017; Tingley et al. 2017; Brown et al. 2019). Steel is better suited for reuse than other construction materials owing to their stable and robust material properties. Steel reuse projects have been realized in the US (Pulaski et al. 2004; Downey 2010), Canada (Gorgolewski et al. 2017), UK (Hradil et al. 2020), EU (Addis 2006; Hradil et al. 2020), and, as discussed later, Japan. The steel industry of UK and EU (Brown et al. 2019) have developed standard protocols to promote steel reuse, while noting that reuse should be limited to steel erected after 1970, that has not been subjected to fatigue, and is free of damage caused by corrosion, fire, high impact, or earthquakes. Hradil et al. (2020) developed a comprehensive procedure to realize widespread reuse in single-story steel buildings.

In the rest of the paper, the state-of-art of steel reuse in Japan is discussed from motivation, relationship with seismic design requirements, technology that aid reuse, material properties, reuse projects, to a proposed design procedure, and future directions. A key notion to the discussion is that, unlike many other parts of the world (Brown et al. 2019), buildings in Japan cannot escape the possibility of experiencing an earthquake within its lifetime.

## Motivation: Why Reuse Steel?

The *Draft Recommendations* (AIJ 2015) recognize the benefits of steel reuse in three categories: natural environment, living environment, and labor environment. The benefit to natural environment is clear. As agreed worldwide (Addis 2006; Dunant et al. 2017; Tingley et al. 2017), the first and foremost reason to pursue steel reuse is to avoid or reduce the energy use and carbon dioxide emission associated with steel recycling. Steel reuse can reduce the pollution associated with mining iron ore and rare metal such as manganese, chromium, nickel, molybdenum, and cobalt. The impact can be understood from statistics that imply that, in Japan, steel manufacturing accounts for 13% of domestic power demand (based on statistics for fiscal year 2018 reported by the METI [2022]), while building construction accounts for 32% of the domestically consumed steel (JISF 2014). The benefit to living environment is achieved through promotion of disassembly over demolition, as shown in Fig. 2, as less noise, less vibration, less air pollution, and thereby, less intrusion to the immediate neighborhood. (Note that many steel buildings are constructed in congested urban areas). The benefit to labor environment may be recognized through providing a potentially more efficient and economical option for material procurement, promoting labor-efficient construction with less reliance on heavy machinery, and promoting record keeping of structural and material information.

Today, some of the above-described benefits of steel member reuse is rewarded by assessment tools such as the AIJ *Recommendations for Life-Cycle Cost Assessment of Buildings* (AIJ 2013a), *Comprehensive Assessment System for Built Environment Efficiency* (*CASBEE*, IBEC 2016), and *Leadership in Energy & Environmental Design* (*LEED*, USGBC 2014). In Japan, *CASBEE* is the primary tool applied to over 26,000 buildings to date. Each of these assessment tools include a category for rewarding green material, for which reused steel qualifies.

## Technology for Disassembly

Wada et al. (1997) have proposed "damage-control" design as the future of seismic design. Initially, the concept was intended for high-rise buildings where the conventional design approach to expect plastic deformation in structural members may not be adequate: the target structural performance should be higher than for ordinary buildings considering the much greater life hazard and more expensive downtime. The damage-control concept addresses such concerns by designating sacrificial structural elements where inelastic action and seismic energy dissipation is concentrated, and proportioning all other structural components to remain elastic, and thereby achieving continuous-use performance and minimizing repair cost after major earthquakes. The concept has played a large role in promoting energy dissipating devices such as buckling-restrained braces, oil dampers, steel shear panels, etc. for use in high-rise steel buildings (above 60 m as defined by the Japanese Building Standard Law) where checking for drift amplitude and plastic deformation by time-history analysis is mandatory.

Iwata and Fujita (2008) proposed a structural system that advances the damage-control concept to meet sustainability goals. The system employs buckling-restrained knee braces in a framing system comprising semi-rigid joints such that, even under a severe earthquake, inelastic action occurs only in the buckling-restrained knee braces. Excellent seismic performance and replaceability of the deformed buckling-restrained knee braces was demonstrated by cyclic-loading tests to story drifts of ±0.04 rad. The primary members are expected to remain damage-free through the service life of the building and might be disassembled by removing PC rods. Kishiki et al. (2004) and Aburakawa (2009) among many others propose various damage-control structural systems that may be suited to achieve exceptional seismic performance and easy disassembly. Similar systems are being developed around the world, for example by Mansour (2011).

Two examples of disassembly technology that have seen real application are highlighted below.

*Helical piles*

Helical piles, which comprise a round-hollow steel section with a spiral steel blade, either of the two types shown in Fig. 3, attached to the bottom end, is one of the primary piling methods used for large-scale facilities. When torque is introduced, the pile penetrates alluvium soil by a screw mechanism. Helical piles offer unique benefits such as minimal noise disturbance, no surplus soil, dry process (no water or cement required), etc., and currently enjoy a 7% market share of all piles in Japanese building construction. The standard size is 30-m in length and up to 1,600 mm in diameter. When penetrating large depth, up to 80 m, the round-hollow steel is spliced typically by complete-joint-penetration groove welds.

An important benefit of helical piles is relative ease in removal. As illustrated in Fig. 4, removal is conducted by (1) exposing the pile cap, (2) killing the friction resistance between the pile body and soil by repeating forward and reverse rotation, then (3) introducing reverse rotation to pull out the pile, and, as needed, (4) gas cutting to length adequate for transportation. The removed pile may be reused after adequate inspection (visual, dimension measurement, mechanical properties) and refurbishing.

Two-thousand helical piles, 114 to 600-mm in diameter, were removed after the Expo 2005 in Aichi, Japan, although unfortunately those piles were disposed before being reused. Reuse of helical piles has been reported from a rapid restoration project of railroad bridge piers tilted after by the 2011 Tohoku earthquake (Iwamoto and Yonezawa 2012). In this project, as indicated in Fig. 5a, 400-mm diameter helical piles were used in temporary reaction systems to jack the piers back to vertical. These piles were subsequently removed, refurbished, and afterwards reused for strengthening the foundations of the same piers, as shown in Fig. 5b.

### *Detachable connections for automated construction*

Ishii and Tanaka (2008) explored the use of cement to achieve rigid connections between circular-tube columns. As shown in Fig. 6, a connection is formed by sliding an upper and lower column, both provided with an end plate, into a connection element comprising a short tube. Inside the tube, the columns rest on a diaphragm plate. Steel wedges are inserted vertically into the gap to adjust the relative position of components and to allow for eventual disassembly. The gap between the columns and connection element is filled with mortar or concrete to achieve integrity. Seismic performance of the connection, which relies on bearing between the elements, has been validated experimentally.

The connection is suited for steel reuse because it is forgiving in erection tolerance, less labor intensive than conventional practice that splice the columns by CJP welds, and allows for easy disassembly. Fig. 7 shows an example where the disassembly procedure was examined in the laboratory. By first removing the wedges, the bond between mortar and steel elements could be broken easily.

## Properties of Structural Steel in the Building Stock

The building stock in Japan was constructed over the last sixty years. As seen in Fig. 8, steel is a common construction material today, but very few steel buildings were constructed prior to 1960. Buildings in Japan may be separated into two eras by structural design requirements: before or after the 1981 amendment of the Building Standard Law. Before the amendment, buildings were designed based on allowable stress requirements. The amended Building Standard Law requires building structures to satisfy two levels of seismic requirements: Level 1 intends to assure that the structural system remains largely undamaged during moderate earthquakes, while Level 2 intends to prevent structural collapse and thereby assure life safety during severe earthquakes (IIBH 2021). Level-1 design calls for allowable stress checks, with a safety factor of unity, against seismic loads typically computed for a base shear coefficient of 0.2. Level-2 design calls for nonlinear analysis against a base shear coefficient of 0.25 to 0.5, depending on the ductility category of system. Historically, Japanese research was influenced by the U.S., as evidenced by the fact that AIJ publications referred to American Institute of Steel Construction (AISC) specifications at the time but modified to meet high seismic demands.

Table 1 summarizes the historical development of structural steels and relevant codes and provisions in Japan. Production of structural shapes started in the mid-1950's. The first Japanese Industrial Standard (JIS) on mechanical and chemical requirements for structural steel was established in 1952. The most common steel was SS and SM steel until SN steel was introduced in 1994. Since the 1990's, a wide array of structural steel has been introduced in the market, although the high-strength variety and low-yield-point steel have not been included in JIS but recognized as material certified by the Minister of Land, Infrastructure, Transport and Tourism (hereinafter referred to as Minister-certified material). Minister certification is a product-by-product, factory-by-factory process to permit use of non-JIS material in building construction. The JIS dimensions and geometric requirements, first established in 1954, has been updated to tighten the dimension tolerance and to introduce a very large number of "universal-depth" beam sections (with universal $d$ dimension rather than universal $h$). Production of square hollow structural sections (HSS) started in the late 1960's. Square HSS produced from SS or SM steel by the formed-from-round process and form-square weld-square process were recognized in 1989 by the Standard of Japanese Society of Steel Construction (JSSC) Standard JSS II 10 as STKC R and P, respectively. More recently, square HSS are produced predominantly from SN steel and are recognized as Minister-certified material, BCR and BCP. Today, BCR is available in sizes up to $h = b = 550$ mm, while BCP is available to $h = b = 1{,}400$ mm. Larger and heavier columns are built up by combining four steel plates with complete-joint-penetration groove welds using a submerged-arc welding process. Since the 1990's, square columns produced by either of the three methods have taken over I-section columns. Over the last three decades, the fabrication and construction methods have remained largely unchanged except for the improvements in connection details after the 1995 Kobe earthquake and increasing tendency in structural design to adopt tighter drift limits to control nonstructural damage during seismic events.

Table 2 summarizes the mechanical and chemical requirements of SS, SM, and SN steel. Some of the older specifications are inherited by newer specifications: SS400 (originally SS41) is nearly equivalent to SN400A, SM400B (originally SM41B) is nearly equivalent to SN400B, and SM490B (originally SM50B) is nearly equivalent to SN490B. SM steel is improved over SS steel in chemical control and weldability. SN steel, which is the most common grade today, introduced yield-to-tensile requirements. Among the three classes of SN steel, class C secures through-thickness properties, class B is suited for primary load-carrying members, class A is not meant for welding and hence should be limited to secondary members.

Table 3 summarizes statistical data collected from mill test reports, available from three different periods, reported by Aoki and Murata (1984), Shimura et al. (2003), and Fujisawa et al. (2013). The average values over a range of plate thickness and shapes are listed. The slight decrease in mean strengths and coefficient of variations (COVs) may be a result of improvement in manufacturing technology. However, the change over a span of 30 years is negligible for the engineering practice. In many regards, the average steel produced in the 1980's meets the current JIS specification for the same strength grade.

If marking cannot be identified and no record of steel grade can be found from design documents or mill test reports, then a safe estimate is that the material is SS400, SN400, or SM400, which are historically the lowest strength grade produced in Japan. Depending on the age of construction, SN400, a grade established in 1994, may be excluded from the possibility. If substantial weldment is applied to the steel, as in beam-to-column moment connections, then the steel is probably SN400B/C or SM400 but probably not SS400.

## Examples of Reuse

Table 4 lists examples in Japan where steel members reclaimed from an older building have been reused in a new building constructed at a different location. These examples were collected by the authors over the last 20 years through involvement in the project, interview and site visit, and/or reported articles. Details of Examples 1, 3, 4 and 5 are reported in the *Draft Recommendations* (AIJ 2015). Example 6 is detailed by Fujita and Okazaki (2018). In all examples, the new building inherited the same use and composition as the original building. In Example 1, six pavilion structures were disassembled after the 2005 Universal Expo (the same Expo event mentioned for helical piles), transported to a different site, and reused to construct a new factory building. The six original structures were designed for possible reuse, but the reuse destination was not predetermined. Examples 2 and 3 were cases where reuse was planned simultaneously with the original use. Examples 2, 3, 5, and 6 were relocation projects with minimal or no alteration in structural configuration and travel distance between 1 and 800 km. Examples 3 and 4 were conducted by house manufacturers whose products comprises standardized cube-framed steel units connected horizontally and vertically by bolting. Theoretically, the steel units are very well suited for reuse because they are designed for disassembly, and the original manufacturer can manage the steel units within a closed circulation system.

In Example 5, a gymnasium (total floor area 1,483 $m^2$) was relocated and reorganized into a new, slightly smaller gymnasium (total floor area 1,089 $m^2$). The new gymnasium was constructed from steel members and external finish reclaimed from the original gymnasium. Although data from mill test reports were lost, member reuse was approved by authority based on evidence of steel grade provided in engineering drawings and calculation records of the original building. The original building had not been exposed to fire or major earthquake. After careful disassembly, each member was visually inspected. It is estimated that the use of reclaimed steel over newly manufactured steel for the new gymnasium resulted in 97% or 180-t reduction in $CO_2$ emission associated with the steel framing system.

In Example 6, a factory (total floor area 1,059 $m^2$) was relocated and reconstructed piece-by-piece into a new, nearly identical factory (total floor area 1,073 $m^2$). Approval by authority was done similarly to Example 4. Because both buildings were near the shore, members reclaimed from the original building were transported to the construction site by barges. After visual inspection, the members were used with minimal repair and alteration. The estimated $CO_2$ reduction associated with the steel framing system is estimated as 96%.

## Design Methodology

### *Different Possibilities of Steel Reuse*

Steel reuse may be categorized into the possibilities illustrated in Fig. 9. The source of member reclamation, i.e., the original building, may be: (A) a building designed for disassembly and reuse; or (B) a building not designed for disassembly and reuse. Examples of (A) are rare but have existed in association with special events such as world expos and international sport events. Case (A) is not unusual for temporary structures with predetermined life. Nonetheless, (B) is the norm for the vast majority of buildings. Considering the fact that, in Japan, the life span for commercial buildings in big cities can be as short as 15 years, and a big proportion of the building stock constructed in the 1970' to 1990's (see Fig. 8) is expected to be replaced in the near future, (B) should be recognized as the primary target.

The new usage of members extracted from (A) or (B) may be: (I) predetermined or (II) yet to be determined at the time of reclamation. Examples of (II) are rare in today's environment, and in fact, cannot be realized without an established scheme for selection and reclamation from an end-of-life building, quality control, and a market for storage and distribution. Among the six examples listed in Table 4, Examples 1 to 4 may fall in (A), while Examples 5 and 6 fall in (B). Example 4 may belong to (II), while all other examples belong to Case (I).

### *Design for Deconstruction and Reuse*

If steel reuse is to become a norm, buildings in the future should be preconditioned accordingly. Key differences from the current norm in design, material procurement, fabrication, construction, use, and demolition are listed below. While item (1) is rather unique due to the high-seismic conditions in Japan, items (2) to (5) are recognized equivocally in many parts of the world (e.g., Pulaski et al. 2004; Hopkinson et al. 2018; ISO 2020).

(1) *Minimize chances of yielding*: Plastic work combined with strain aging will, in general, increase yield strength, reduce ductility, and produce residual deformation of the steel members. Therefore, ideally, members targeted for reuse should remain elastic during service such that confidence in reusability is secured and the number of reusable members is maximized. Damage-control seismic design and seismic isolation align very well with this goal, however, on the other hand, there is a limit to the extent such techniques can be applied to ordinary buildings.

(2) *Design for disassembly*: Design for disassembly is essential to make member reclamation feasible, and thereby, steel reuse feasible. Most importantly, the connections between members should be made for easy disassembly and reclamation. Fire protection applied

by wrapping or board attachment is preferred over spraying to allow for easy removal.

(3) *Standardize and Modularize*: Floor height and distance between column centers shall be, to the extent possible, standardized such that the proportion of beams and columns with reusable dimensions is maximized.

(4) *Secure material traceability*: In order to prepare for eventual reuse, data on location, geometry, grade, mechanical properties, chemical composition, etc. for all primary members shall be compiled and stored in a "building record file."

(5) *Service life planning*: Today, buildings that are designed for component reuse tend to be those planned for a predetermined service life. For such buildings, a different practice in design and management might be adopted, for example, reduced design loads, relaxed durability and maintenance requirements may be justified by knowledge of a specified service life and use. Such practice shall promote short-term land use by permitting optimized design solutions, lower construction cost, temporary solutions to temporary overload situations (for example, by setting rules to remove snow beyond an accumulation limit; add braces when wind speed limits are exceeded, etc.), and new technology. The AIJ *Recommendations for Design of Buildings with Predetermined Service-life and Conditions of Use* (AIJ 2013b; synopsis provided in AIJ [2021]) proposes a comprehensive guideline to benefit from the knowledge of service life, short or long.

### *Reuse of Steel Reclaimed from End-of-Life Buildings*

In today's condition, effort should be focused on establishing a standard procedure for reuse category (B)-(I), i.e., extracting members from an original end-of-life building, which is not designed for disassembly and reuse, when the destination for reuse is known at the time of disassembly. In fact, this is the category on which abundant study on steel reuse (Gorgolewski et al. 2017; Dunant et al. 2018; Hopkinson et al. 2019) have focused.

Fig. 10 summarizes the engineering process for such cases. While Hradil et al. (2021) present an engineering process specialized for single-story steel buildings, the scope of Fig. 10 is applicable for general steel buildings, from single-story buildings to multi-story office buildings. At the planning stage, access to members targeted for reuse may be limited because the building is in use, and/or the members are shielded by architectural finish and fire proofing. The preliminary assessment on reusability shall be based on document review and visual inspection, and therefore, expected to be no more than a presumption. Therefore, a second, more thorough assessment shall be made after the members are extracted.

The engineer shall be involved with the project starting from master plan, preliminary assessment, structural design, environmental evaluation, disassembly, reassessment after reclamation, construction, and building record compilation. Fig. 11 provides a detailed breakdown of the engineering process, while some of the key issues are described in the following. Environmental evaluation shall be conducted at three different stages, each using a green building certification program.

(1) Preliminary Survey and First Environmental Evaluation

Prior to disassembly of the original building, the engineer shall set environmental impact goals and conduct a first environmental evaluation on whether those goals might be achieved by the preliminary reuse plan. The following information shall be collected on structural members that may be reused:

- Location, geometry, material designation, and connections
- Daily service condition
- Changes from engineering drawings such as permanent deformation, rust, unplanned web opening
- Notable history of fire, earthquake, wind, snow, ground subsidence, repair, etc.

- External finish such as fire proofing, paint, chemical treatment, with attention to toxic substances

The collection shall be based on review of as-built drawings and documentation submitted for plan approval. Members targeted for reuse shall be identified, and the need of field survey shall be determined. (Note that if a complete building record file is available, as in the proposed precondition for future buildings, then this survey may be readily conducted based on the record file.) If deemed necessary, visual inspection shall be made to collect additional information. Based on the information available, the targeted members shall be assessed for material designation or grade, degradation in structural properties, and thereby, suitability for reuse.

(2) Structural Design and Second Environmental Evaluation

The design limitations of the reused members shall be determined based on the assessment results: members whose material designation cannot be identified or members that show evidence of mild deformation or fire exposure shall be designed to remain elastic. At the other extreme, members that possess the same properties and confidence as newly manufactured steel may be designed for elastic-plastic behavior. Members that do not fall in either category may be designed for downgraded strength and/or ductility depending on the confidence established by the preliminary assessment. Research need is recognized to establish the relationship between use history, possibly including overloading and seismic effects, and remaining elastic-plastic performance of steel members.

Based on the structural design, a second environmental evaluation shall be conducted to recognize the benefits of the reuse plan.

(3) Reclamation and Reassessment

Appropriate disassembly shall be conducted to extract the target members efficiently yet without damage. The reclaimed members shall be reassessed whether their properties match the prior presumption. The reassessment shall be based on thorough visual inspection and, if deemed necessary, extracted tension coupons. Portions that are deformed beyond tolerance, rusted, or protruded may be repaired or removed. Members that are not suited for reuse shall be sorted for recycling. Some members may be reused after repair and under updated design assumptions.

(4) Construction

The same construction method as in any ordinary buildings shall adopted. It is cautioned that some of the reclaimed members that passed the preliminary assessment may not pass the reassessment, and therefore, new members may be required for replenishment. Before the project is completed, data on all structural members shall be updated and compiled to prepare for future reuse.

(5) Data Management and Third Environmental Evaluation

A third and final environmental evaluation shall be conducted at completion of the new building in order to recognize the environmental impact of steel reuse. A comprehensive building record file shall be produced to compile data on geometry, material grade, history of fire or overload, and reusability assessment results for individual members, preconditioning for reuse including design for disassembly, complete engineering record of the building, and environmental evaluation records.

During the service life of the building, the building record file shall be updated whenever the building is altered or experiences extreme events. If this record file were available, then Procedures (1) and (2) could be conducted with no additional effort.

The above-described procedure was, in general, followed in the reuse examples listed in Table 4. In all examples, the original building had no history of fire or overload, reclaimed members were reused in the primary load-resisting system, careful disassembly was conducted to extract the targeted members damage free, and an environmental evaluation was conducted either at the start and/or end of the project. Therefore, the proposed procedure should be directly applicable to the current Japanese practice, and it could be understood as a clarification of what should be done to achieve a successful reuse project.

## Future Directions

The following six items are identified as the key to promoting wide acceptance of steel member reuse.

1. *Establish a procedure to quantify the remaining structural performance of degraded steel*
2. *Establish connections designed for disassembly*
3. *Incorporate member reuse in green building certification*
4. *Introduce modularized structural systems*
5. *Establish a commercially feasible market*
6. *Secure traceability of steel*

The six items have been discussed extensively in the literature. Item (5) has been identified as the most significant barrier by many studies (Addis 2006; Dunant et al. 2017; Tingley et al. 2017; Hopkinson et al. 2019). Item (2) is addressed by research to develop deconstructable and reusable composite slabs (Gritsenko et al. 2019; Jakovljević et al. 2020), and proposed connections that minimize welds and rely instead on bolts (Hradil et al. 2021). Item (3) is discussed extensively by Pongiglione and Calderini (2015). Item (4) is recognized by Pulaski et al. (2004) and ISO (2004). Item (6) is emphasized by Hradil et al. (2014), Brown et al.

(2021) and ISO (2020). The following discussion emphasizes the significance of each item and associated challenges for Japanese construction.

*(1) Establish a procedure to quantify the remaining structural performance of degraded steel*: If convincing evidence is available to prove that a member reclaimed from an older building possesses the same mechanical properties as newly manufactured steel, then the member may be used similarly as new steel. If no authentic record, in form of mill test report or record file as described later, is available, then the reclaimed member may be limited for use in the elastic domain as floor beams or other secondary members. A conservative estimate shall be used for their yield strength: In Japan, 235 N/mm$^2$ shall be adequate because this has been the minimum specified yield strength since the establishment of JIS. If imperfection beyond tolerance, whitening by fire, or substantial area loss due to rust is detected by visual inspection, then the reclaimed member is not suited for reuse and therefore should be recycled.

However, there is a lack of scientific evidence to judge the appropriate use of reclaimed members that may be degraded. Research is needed to understand the change in mechanical properties over life cycle, due to fabrication, construction, reclamation as well as condition of use. The *Draft Recommendations* propose a concept of using reduction factors to address degradation in strength and ductility but falls short of providing specific values for the factors. The causes of degradation include: (a) post-yield deformation due to overload or seismic effects combined with strain aging; (b) fatigue due to large number of stress cycles; (c) fire; (d) corrosion; (e) weld; (f) plastic work introduced during manufacturing (forming) and fabrication (cambering); and (g) thermal loading cycles. The degradation caused by each of these causes must be quantified before the reduction factors mentioned above may be established. Among the seven causes, (a) is believed to be by far the most significant for Japan: Steel members in Japan experience earthquakes with high likelihood during use because the entire country is in high-seismicity region, and steel construction tends to adopt full moment frames where all primary members participate in lateral load resistance. A measure is needed to quantify the remaining seismic performance of steel members based on evidence such as residual story drift, residual member deformation, and visual appearance.

*(2) Establish connections deigned for disassembly*: The member targeted for reuse should be reclaimed by disassembly process that introduces minimal or no damage. The expense of removing the composite slab (Fujita and Iwata 2008; Gritsenko et al. 2019) presents a major concern for extracting beams from existing buildings. The adoption of rigid connections at all beam-to-column nodes, achieved by complete-joint-penetration groove welds and occasionally slip-critical bolted joints, poses a unique challenge to Japan. Future buildings shall adopt new designs that allow for disassembly. To be specific, rigid connections should be minimized, and those rigid connections should preferably be achieved by bolting rather than welding, and by bearing connections rather than slip-critical connections. A mechanism other than welded shear studs that allow for deconstruction should be adopted for composite reinforced-concrete slabs. Such change in construction scheme is expected to promote prefabrication and modularization, and thereby transform construction technology towards improved labor conditions and productivity.

*(3) Incorporate member reuse in green building certification*: Social incentive is necessary to draw public attention towards steel reuse. Although green building certification programs have proven effective to promote sustainable design strategies, the leading Japanese program CASBEE (IBEC 2016) remains hesitant to reward structural member reuse, on the basis that, in many measures and statistics, construction plays a smaller role than operation in the life-cycle environmental impact of a building. It is noted that the recognition is shared internationally (e.g. Pongiglione and Calderini 2015) but has not prevented programs such as LEED (USGBC 2014) to promote steel reuse proactively. Therefore, there is a substantial room

for improvement in Japan: an independent certification might be needed to rightfully reward the contributions of steel member reuse to the natural environment, living environment, and labor environment.

*(4) Develop structural systems that are suited for member reuse*: For many years, reuse has been common in the construction industry for shoring, scaffolding, temporary stadium seating, event tents, and other short-term facilities. These structures are composed of members of limited types and dimensions. Take for example shoring for ground excavation: the Japanese industry uses I-sections with $h = b = 200$ to 500 mm, with H-350×350×10×15 and H-350×350×12×19 being by far the most widely circulated. As mentioned for Examples 3 and 4 in Table 4, the prefabricated house manufacturers have established a scheme to circulate their standardized cube-framed steel units after repair and refurbishment. Similarly, the potential sources of reclaimed steel and their consumers may be maximized by further standardizing, or modularizing steel buildings. Features required for reusable members are: standardized dimensions, longer rather than shorter length, I-sections as opposed to tubular sections, minimal attachments, holes or stiffeners. It is acknowledged that, unfortunately, the Japanese construction industry has been moving in the exact opposite direction to these requirements. A breakthrough idea that does not conflict with the current norm of the construction industry is needed.

*(5) Establish a commercially feasible market*: An effective storage and distribution system must be established to make procurement of reclaimed steel as fast and economical as newly manufactured steel. Because, in Japan, such distribution system does not exist, and no supplier of reused steel exists, successful examples of steel reuse have been limited to special cases where the engineer had full access to data of an end-of-life building, the planned building was similar in use and size to the end-of-life building, and the new building was constructed as the end-of-life building was being demolished. In order to make steel reuse a

norm, reclaimed steel must be purchased upon disassembly, inspected and stored for eventual distribution. Intervention by policy makers may be required to initiate the new market.

*(6) Secure confidence of steel*: The current practice is to base confidence in delivered steel on mill test reports. However, in Japan, mill test reports are seldom stored for the life span of a building. As evidenced in the examples of reuse, Examples 5 and 6, the reports along with engineering data can be lost by the time the building is at the end of its useable life. The confidence in reclaimed steel hinges, in addition to the original engineering records, on the history of service, reclamation, repair, and associated changes in material properties. Storage of such life record is difficult today but may become feasible with the advent of information and communication technology. Highly reliable structural management may be possible by combining Building Information Management (BIM) with structural health monitoring to trace the condition of the structural system as well as individual members. Such management record should be useful in knowing and evaluating the condition of structural members, and thereby identifying reusable members, when the building is at the end of its life. Therefore, as recognized by ISO (2020), the issue of material confidence might be naturally resolved as BIM evolves.

## Summary

This paper describes the state of the art of steel member reuse in Japan. Some of the key observations and developments are summarized below.

1. Although strong interest in steel reuse has been shared by the government, industry and research community, very few reuse projects have been realized to date. The AIJ is taking a leadership role to make steel reuse a wide-accepted reality in Japan.

2. Steel construction became common in the 1960’s. Since that time, the minimum specified

strength of the lowest grade steel has always been 235 N/mm$^2$. Little change in mean and coefficient of variation is seen since the 1980's. Control of weldability and yield-to-tensile ratio has improved over years, especially due to the introduction of SN steel in 1994.

3. A design procedure is proposed for reuse projects where the source of member reclamation and destination of reuse are both known. The procedure requires active involvement of the structural engineer in planning, material procuring and execution. Record keeping and environmental evaluation are key to the success of such projects.

4. Six directions are identified to promote steel reuse. Among those directions are research needs to establish a procedure to quantify the remaining structural performance of reclaimed steel, establish connections designed for disassembly, and develop modularized structural systems. Steel reuse in Japan faces a unique challenge posed by high seismicity and the general practice to adopt full moment frames.

## Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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**Table 1. Historical development of structural steel and design provisions in Japan**

| Products | | | | Codes, Standards, Provisions | |
|---|---|---|---|---|---|
| Grade | I-Sections | Square-HSS | Round-HSS | AIJ | BLJ |
| 1952 JIS G 3101 (SS steel) | | | | 1950 Calculation Standard for Steel Structures | |
| | 1954 JIS G 3192 | | | | 1950 BSL enforced |
| 1952 JIS G 3106 (SM steel) | | | | | |
| | | | 1961 JIS G 3444 (STK) | | 1961 Specific block system introduced |
| | 1964 Production of jumbo sections | | | | |
| | 1966 new sections added to JIS G 3192 | | | | |
| | | 1966 JIS G 3466 (STKR) | | | |
| | | Late 1960's Production by formed-from-round process started | | | |
| | | Mid 1970's Production by form-square weld-square process started | | | |
| | | | | | **1981 Two-level design introduced** |
| | | | | 1970 Design Standard for Steel Structures | |
| | | | | 1975 Recommendations for the Plastic Design of Steel Structures | |
| | | | | 1980 Recommendations for Stability Design of Steel Structures | |
| | 1989 Production of constant-depth sections | | | | |
| | | 1989 JSS II 10 (STKC R/P) | | | |
| | 1990 JIS G 3192 updated (web tolerance tightened) | | | | |
| 1991 MC-TMCP steel | | | | | |
| | 1994 JIS G 3192 updated (r-tolerance tightened) | | | | |
| 1994 JIS G 3136 (SN steel) | | | | | |
| | | 1995 Ministry-approved BCR | | | |
| | | 1995 Ministry-approved BCP | | | |
| 1996 Ministry-approved Grade 590 steel | | | 1996 JIS G 3475 (STKN) | | |
| | | | | 1998 Recommendation for Limit State Design of Steel Structures | |
| 2000 Ministry-approved LYP steel | | | | | 1998 Performance-based design introduced |
| | 2005 JIS G 3192 updated (10 sections added 1 section removed) | | | | |
| | 2008 JIS G 3192 updated (flange tolerance tightened) | | | | |
| 2009 Ministry-approved Grade 780 steel | | | | 2009 Manual for Re-using structural members | |
| | 2014 JIS G 3192 updated (added universal-depth sections) | | | 2013 Recommendation for Design of KIGEN-TSUKI Structures | |
| | | | | 2014 Recommended Provisions for Seismic Damping Systems applied to Steel Structures | |
| | | | | 2015 Recommendations for Sustainable Steel Building Construction (Draft) -Member Reuse- | |

Note: Japanese Industry Standards (JIS)

| | | | |
|---|---|---|---|
| JIS G 3101 | Rolled steels for general structure | JIS G 3106 | Rolled steels for welded structure |
| JIS G 3136 | Rolled steels for building structure | JIS G 3192 | Dimensions, mass and permissible variations of hot rolled steel sections |
| JIS G 3444 | Carbon steel tubes for general structure | JIS G 3466 | Carbon steel square and rectangular tubes for general structure |
| JIS G 3475 | Carbon steel tubes for building structure | | |

Standard of Japanese Society of Steel Construction (JSS)

| | |
|---|---|
| JSS II 10 | Cold formed rectangular hollow section steel columns |

**Table 2. Tensile and chemical requirements for typical Japanese steel**

| Designation | Tensile Requirements | | | | Chemical Requirements | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Yield Strength [N/mm$^2$] | Tensile Strength [N/mm$^2$] | Yield-to-Tensile Ratio [%] | Elongation [%] | C | Si | Mn | P | S |
| | | | | | Composition, max, % | | | | |
| SS41 | min 226 | 402 to 490 | N.A. | N.A. | N.A. | N.A. | N.A. | 0.060 | 0.060 |
| SS50 | min 275 | 490 to 588 | N.A. | N.A. | N.A. | N.A. | N.A. | 0.060 | 0.060 |
| SM41A | min 226 | 402 to 490 | N.A. | N.A. | 0.23 | N.A. | N.A. | 0.040 | 0.050 |
| SM41B | min 226 | 402 to 490 | N.A. | N.A. | 0.20 | 0.35 | 1.20 | 0.040 | 0.050 |
| SM41C | min 226 | 402 to 490 | N.A. | N.A. | 0.18 | 0.35 | 1.40 | 0.040 | 0.040 |
| SM50A | min 314 | 490 to 588 | N.A. | N.A. | 0.20 | 0.55 | 1.50 | 0.040 | 0.040 |
| SM50B | min 314 | 490 to 588 | N.A. | N.A. | 0.18 | 0.55 | 1.50 | 0.040 | 0.040 |
| SM50C | min 314 | 490 to 588 | N.A. | N.A. | 0.18 | 0.55 | 1.50 | 0.040 | 0.040 |
| SS400 | min 235 | 400 to 510 | N.A. | min 21 | N.A. | N.A. | N.A. | 0.050 | 0.050 |
| SM400A | min 235 | 400 to 510 | N.A. | min 22 | 0.23 | N.A. | N.A. | 0.035 | 0.035 |
| SM490A | min 315 | 490 to 610 | N.A. | min 21 | 0.20 | 0.55 | 1.65 | 0.035 | 0.035 |
| SM490B | min 315 | 490 to 610 | N.A. | min 21 | 0.18 | 0.55 | 1.65 | 0.035 | 0.035 |
| SN400A | min 235 | 400 to 510 | N.A. | min 21 | 0.24 | | | 0.050 | 0.050 |
| SN400B | 235 to 355 | 400 to 510 | max 80 | min 22 | 0.20 | 0.35 | 1.50 | 0.030 | 0.015 |
| SN400C | 235 to 355 | 400 to 510 | max 80 | min 22 | 0.20 | 0.35 | 1.50 | 0.020 | 0.008 |
| SN490B | 325 to 445 | 490 to 610 | max 80 | min 21 | 0.18 | 0.55 | 1.65 | 0.030 | 0.015 |
| SN490C | 325 to 445 | 490 to 610 | max 80 | min 21 | 0.18 | 0.55 | 1.65 | 0.020 | 0.008 |

Note: Steel SS41, SS50, SM41 and SM50 are historical designations (dated 1959) that were replaced by SS400, SS490, SM400, SM490, respectively, in 1994. The listed values are for $t \leq 38$ mm for the historical designations and for $16 \leq t \leq 50$ mm for the current designations. Elongation is based on tension coupon type JIS 1A.

**Table 3. Statistical data of mechanical properties**

| Year | Designation | Type | Number of Samples | Yield Strength [N/mm$^2$] | | Tensile Strength [N/mm$^2$] | | Elongation [%] | | Yield-to-Tensile Ratio [%] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mean | COV | Mean | COV | Mean | COV | Mean | COV |
| 1984 | SS400 | Mixed | 6,314 | 313 | 35.0 | 450 | 19.9 | 29.8 | 3.9 | 69.5 | 6.4 |
| | SM400A | Mixed | 922 | 308 | 29.6 | 447 | 19.1 | 29.6 | 3.0 | 68.8 | 5.1 |
| | SM490A | Mixed | 3702 | 386 | 37.5 | 539 | 20.6 | 24.0 | 2.3 | 71.5 | 5.1 |
| | SM490B | Mixed | 277 | 375 | 30.4 | 543 | 31.8 | 29.0 | 4.6 | 69.1 | 4.3 |
| 2003 | SN400A | Shape | 872 | 307 | 21.0 | 442 | 12.3 | 32.0 | 2.1 | - | - |
| | SN400B | Shape | 2,291 | 306 | 18.0 | 440 | 11.5 | 32.8 | 1.8 | 69.6 | 3.2 |
| | SN490B | Shape | 5,262 | 388 | 20.2 | 528 | 12.3 | 30.5 | 1.6 | 73.5 | 2.9 |
| | SN490C | Shape | 110 | 386 | 22.6 | 532 | 14.9 | 30.3 | 1.8 | 72.5 | 3.3 |
| | SN400A | Plate | 1,706 | 293 | 21.3 | 442 | 15.6 | 30.0 | 2.8 | - | - |
| | SN400B | Plate | 11,330 | 295 | 18.7 | 443 | 13.5 | 31.2 | 2.9 | 65.9 | 8.7 |
| | SN400C | Plate | 933 | 291 | 15.1 | 440 | 12.1 | 32.3 | 2.7 | 65.7 | 5.7 |
| | SN490B | Plate | 58,944 | 384 | 21.6 | 530 | 13.8 | 27.8 | 2.7 | 71.9 | 3.6 |
| | SN490C | Plate | 15,078 | 379 | 22.1 | 530 | 13.8 | 29.3 | 3.0 | 71.3 | 3.6 |
| 2013 | SN400A | Shape | 551 | 303 | 15.8 | 436 | 11.2 | 32.3 | 2.1 | - | - |
| | SN400B | Shape | 5,816 | 305 | 15.3 | 439 | 13.3 | 32.8 | 2.0 | 69.5 | 2.7 |
| | SN490B | Shape | 14,522 | 392 | 21.5 | 530 | 9.3 | 30.5 | 1.7 | 73.9 | 3.3 |
| | SN490C | Shape | 26 | 372 | 19.8 | 528 | 7.8 | 29.3 | 2.3 | 70.5 | 3.1 |
| | SN400A | Plate | 118 | 298 | 18.5 | 438 | 11.0 | 33.0 | 1.8 | - | - |
| | SN400B | Plate | 2,187 | 300 | 19.0 | 441 | 12.6 | 32.6 | 2.1 | 67.9 | 3.4 |
| | SN400C | Plate | 178 | 305 | 17.7 | 444 | 13.1 | 33.6 | 2.2 | 68.7 | 3.0 |
| | SN490B | Plate | 11,302 | 385 | 21.2 | 531 | 11.8 | 28.4 | 2.1 | 72.4 | 3.4 |
| | SN490C | Plate | 659 | 383 | 21.6 | 534 | 10.6 | 29.6 | 2.5 | 71.7 | 3.5 |

**Table 4. Examples of building constructed from reclaimed steel**

| Ex. | Reuse Category | Original Building | | | New Building | | | Comment |
|---|---|---|---|---|---|---|---|---|
| | | Use | Material and Floor Area | Completion | Use | Material and Floor Area | Completion | |
| 1 | (A)-(I) | Expo pavilion | Steel, 1-story, 3×1,300 m$^2$ + 1× 980 m$^2$ + 1×650 m$^2$ + 1×330 m$^2$ | Mar. 2005 | Factory | Steel, 2-story, 7,854 m$^2$ | Apr. 2007 | Reuse pre-determined for Expo 2005 |
| 2 | (A)-(I) | Event hall | Timber and steel (1-story), Timber (2-story), Steel (1-story), total 1,633 m$^2$ | Oct. 2019 | Exhibition hall | Timber and steel (1-story), Timber (2-story), Steel (1-story), total 1,633 m$^2$ | July 2021 | Reuse pre-determined |
| 3 | (A)-(I) | Store | Steel, 1-story, 167 m$^2$ | Sept. 2006 | Store | Steel, 1-story, 167 m$^2$ | Mar. 2007 | Test case |
| 4 | (A)-(II) | Residence | Steel, 2-story, 147 m$^2$ | Oct. 1980 | Residence | Steel, 2-story, 129 m$^2$ | May 2009 | One of many cases |
| 5 | (B)-(I) | Gymnasium | Steel, 1-story, 1,483 m$^2$ | Aug. 1991 | Gymnasium | Steel, 1-story, 1,089 m$^2$ | Mar. 2000 | |
| 6 | (B)-(I) | Factory | Steel, 1-story, 1,059 m$^2$ | 2009 | Factory | Steel, 1-story, 1,073 m$^2$ | 2015 | |

Note: Reuse Category refers to the definitions in Fig. 9.

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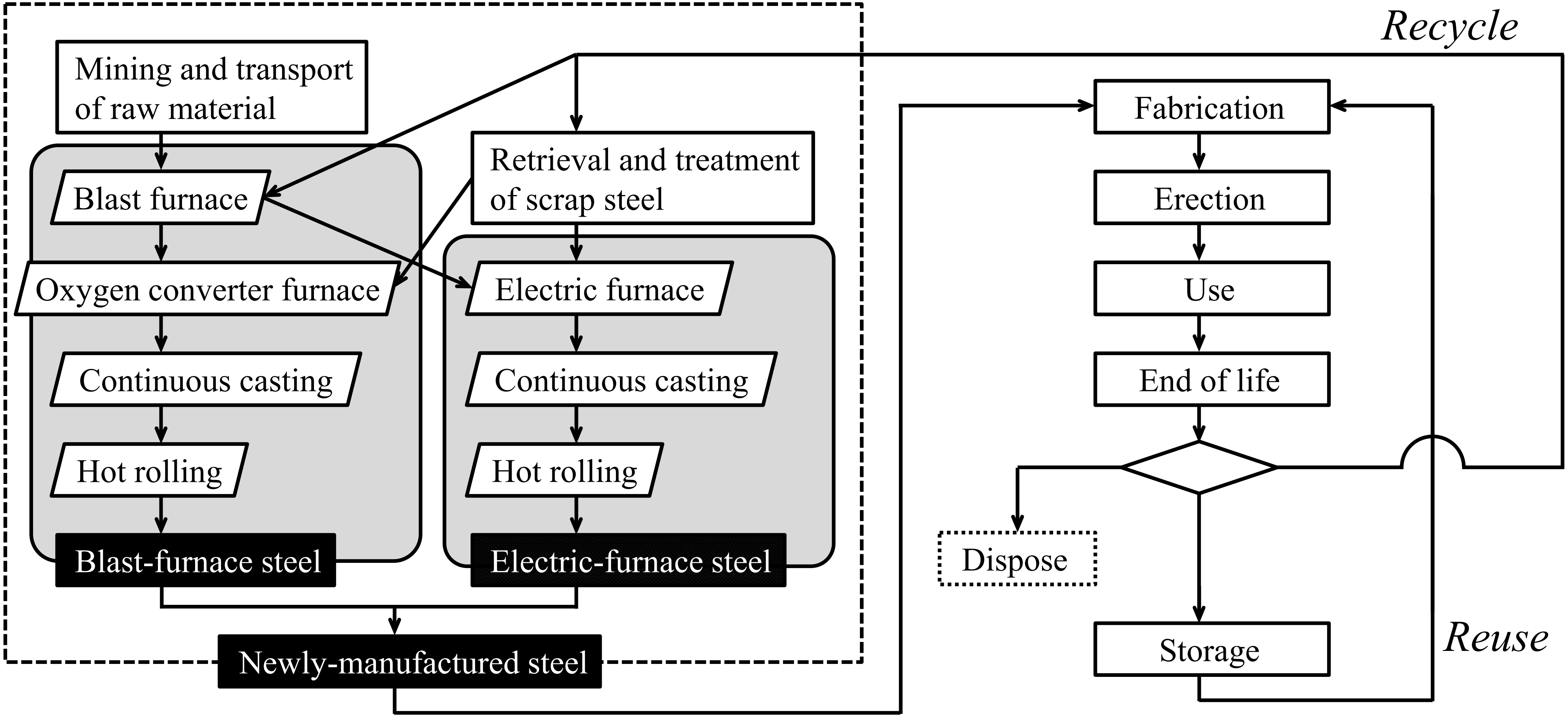


Fig. 1 Circulation of structural steel.


(a) (b)

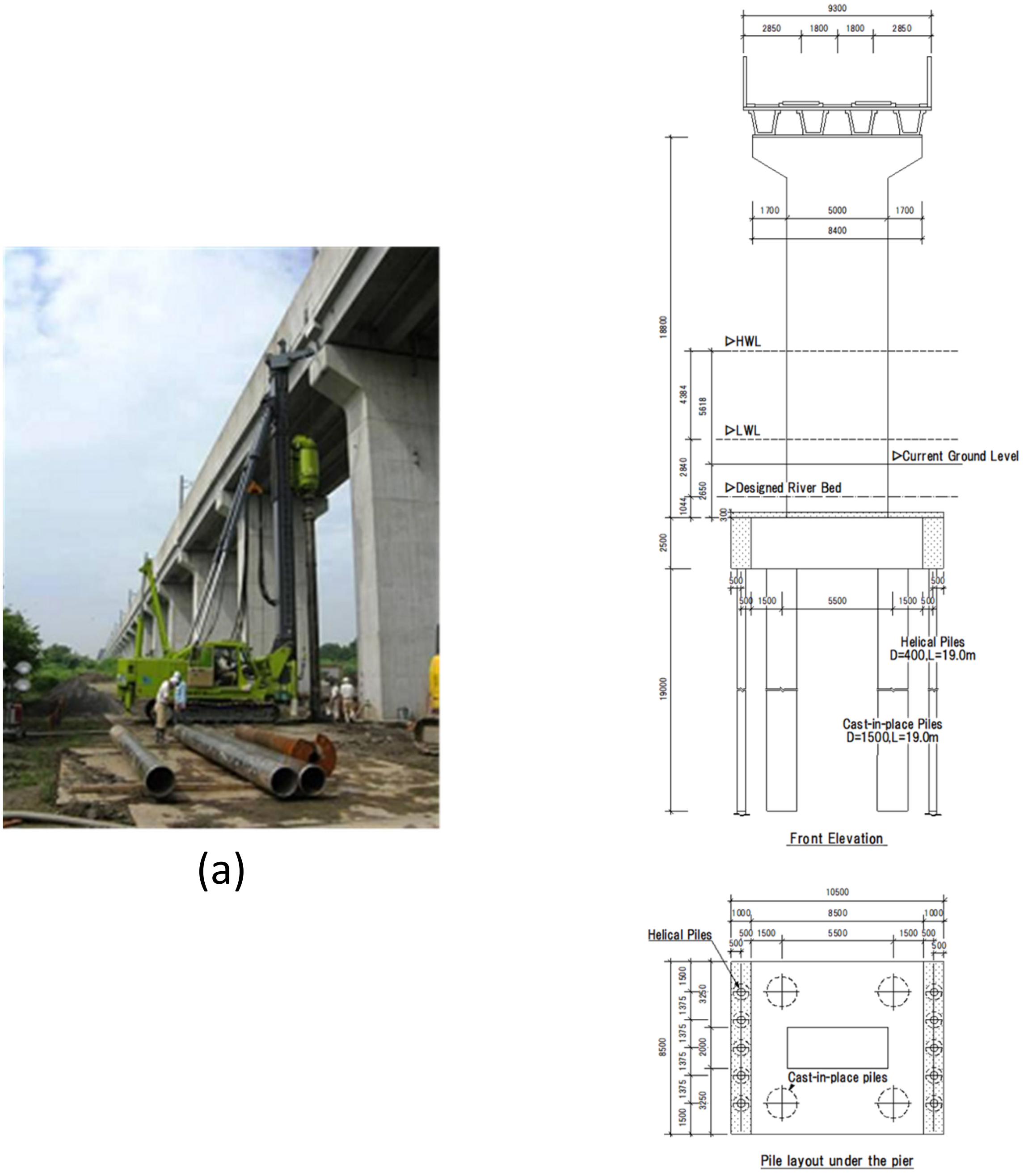
Fig. 2 (a) Steel building demolition; versus (b) disassembly.

(a) (b)

Fig. 3 Types of steel spiral blades in helical piles: (a) continuous spiral (Courtesy of Association of NS ECO-PILE method); and (b) alternating spiral (Courtesy of JFE Steel Corporation).


(a) (b)

Fig. 4 Removal procedure of 900 to 1100 mm-diameter helical piles: (a) operation; and (b) steel blade in sound condition after removal. (Courtesy of Association of NS ECO-PILE method).



(a)

(b)

Fig. 5 Example of helical piles reuse: (a) 400 mm-diameter piles removed after straightening bridge piers (Courtesy of Association of NS ECO-PILE method); and (b) strengthened foundation footing. (Courtesy of Metropolitan Intercity Railway Company [Iwamoto and Yonezawa 2012]).

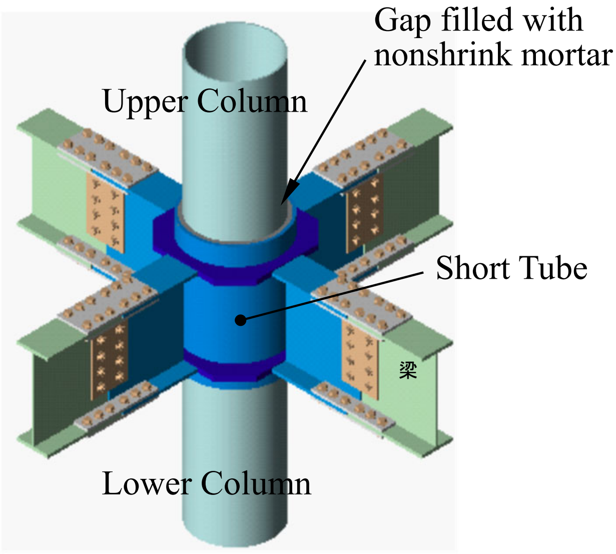


Fig. 6 Composition of detachable connection.

(a) (b)

Fig. 7 Connection disassembly procedure: (a) wedge removal; (b) upper and lower columns separated.

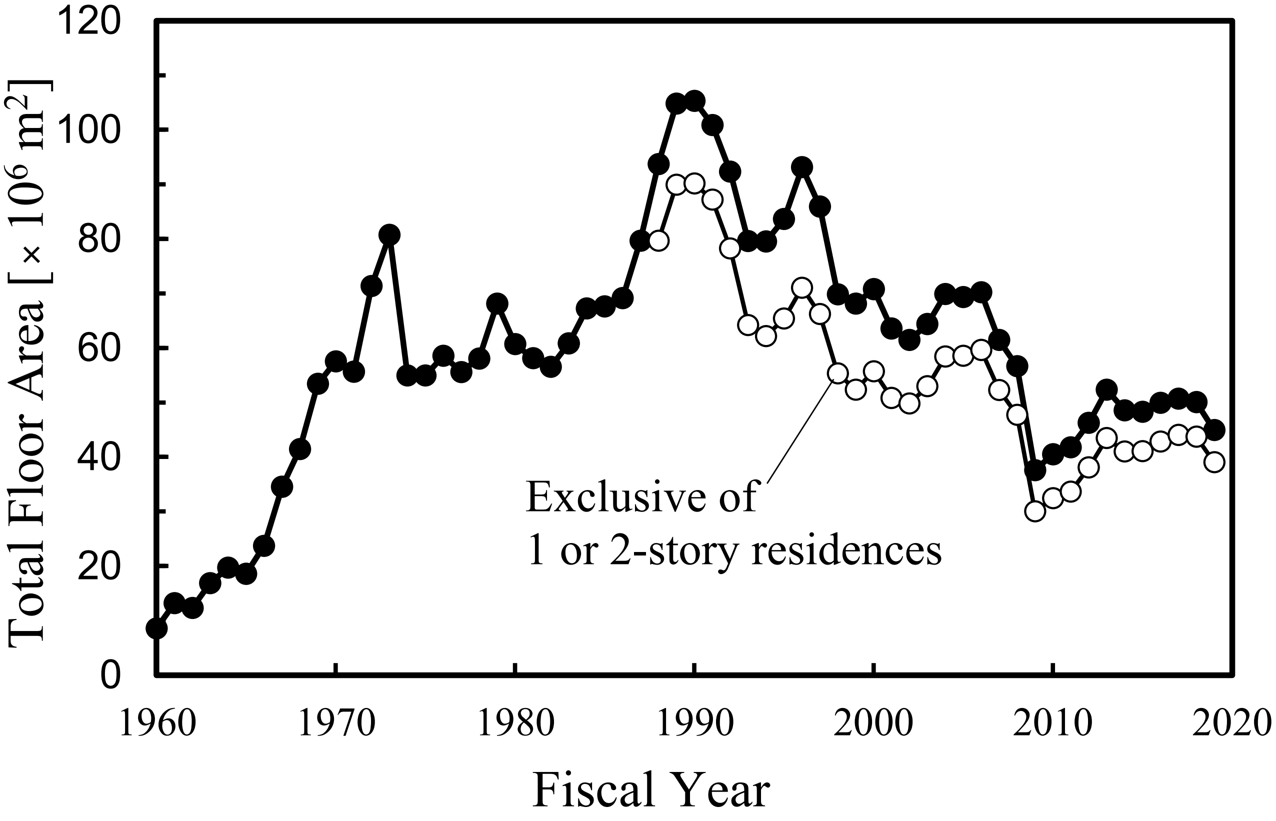


Fig. 8 Steel building construction since 1960 in terms of floor area (Produced from data by MLIT, 2021).

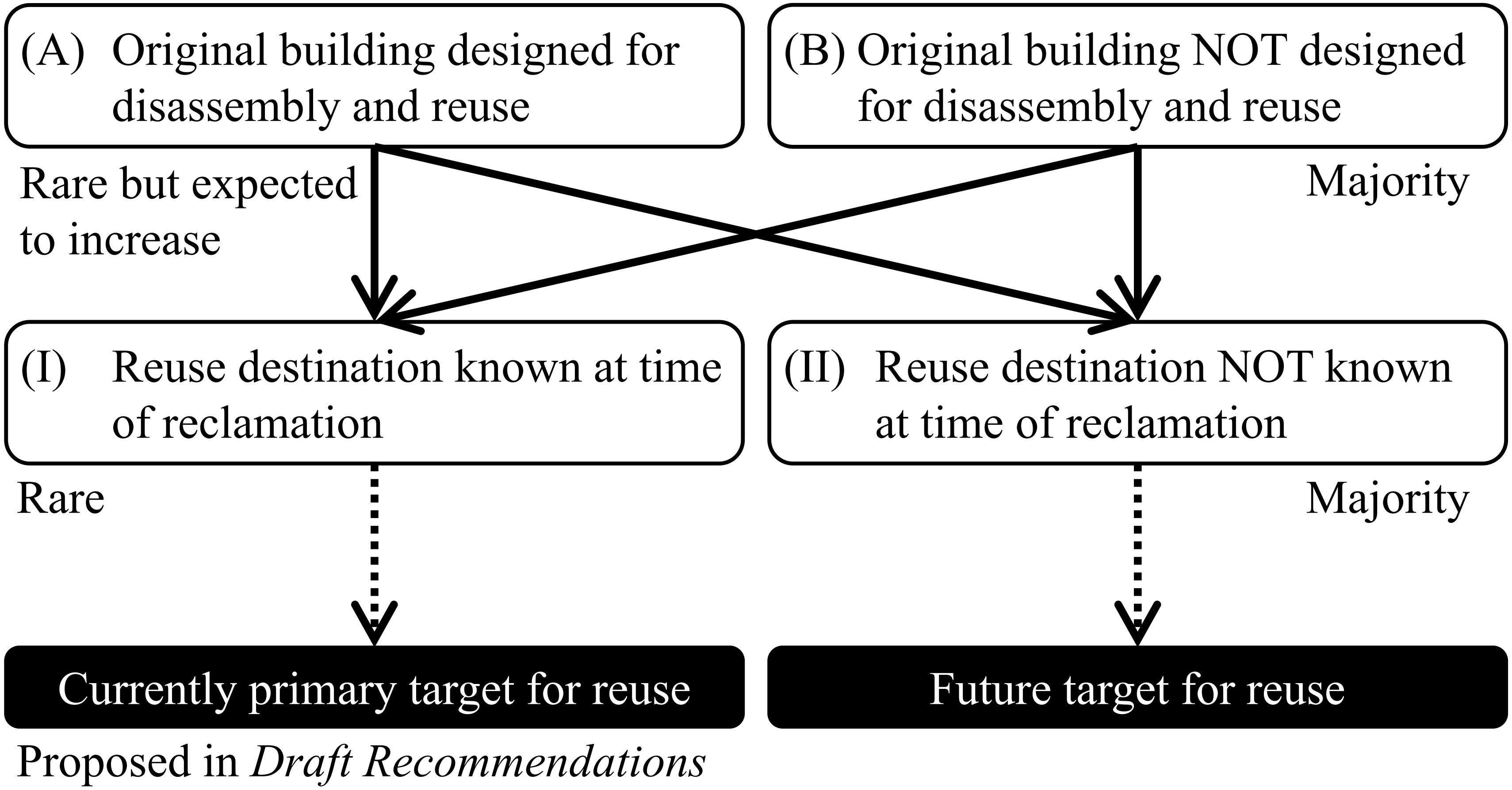


Fig. 9 Categories of steel reuse projects.

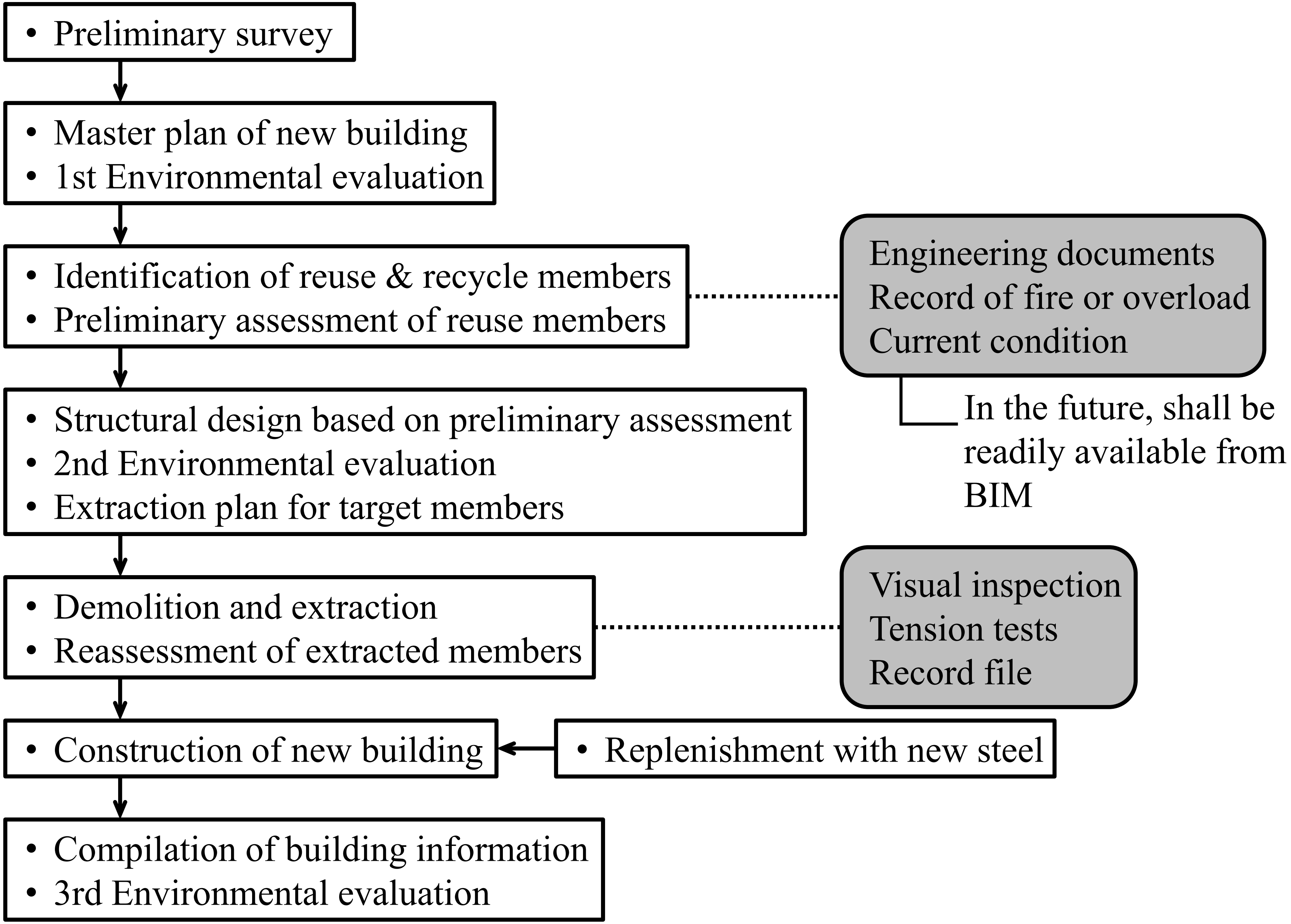


Fig. 10 Engineering procedure for steel reuse.

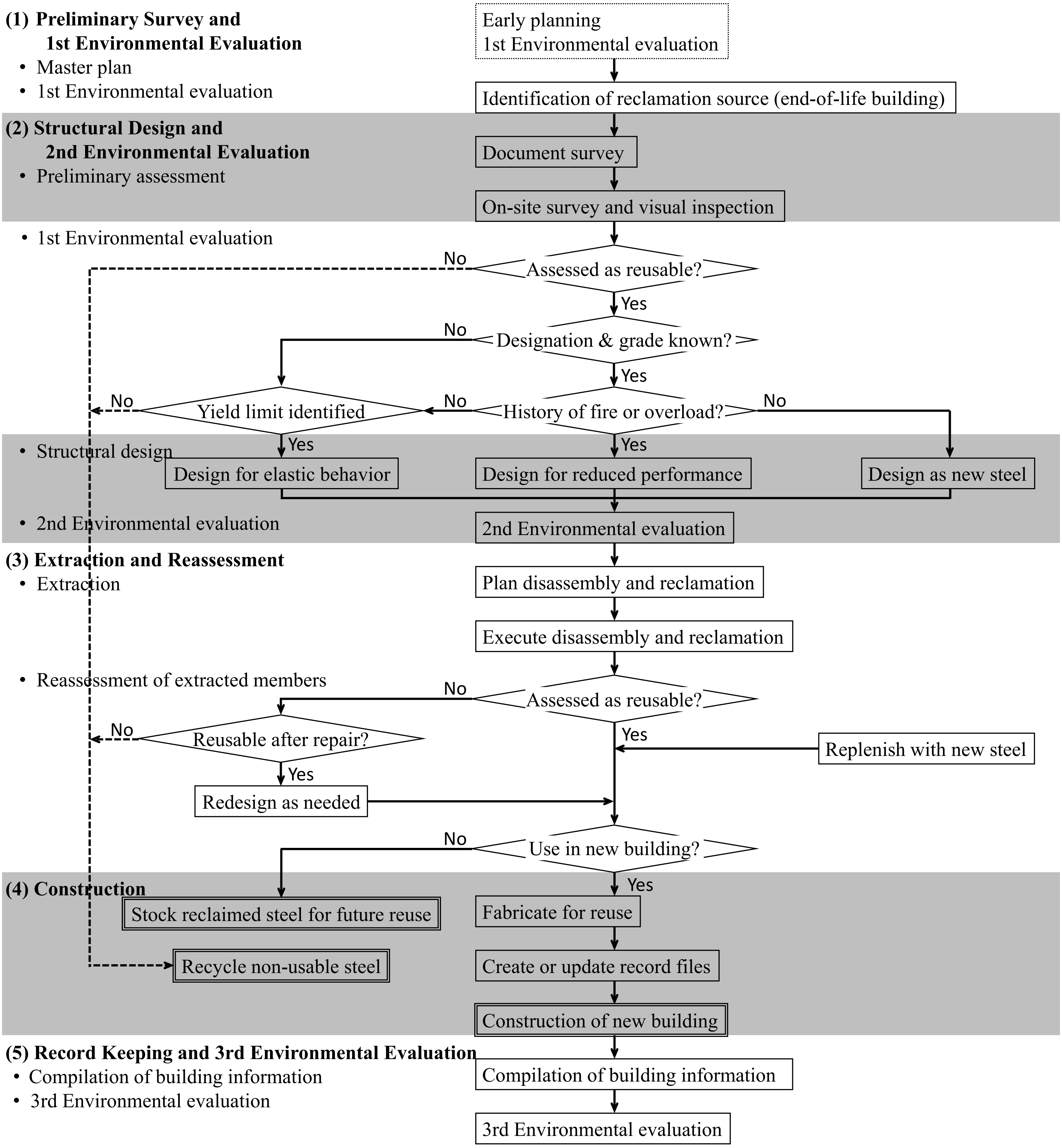


Fig. 11 Engineering procedure when the destination of reclaimed steel is predetermined.