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Author(s)	Fujita, Masanori; Fujita, Tetsuya; Iwata, Mamoru; Iwata, Yoshihiro; Kanemitsu, Tomomi; Kimura, Urara; Koiwa, Kazuhiko; Midorikawa, Mitsumasa; Okazaki, Taichiro; Takahashi, Satoshi; Tanaka, Teruhisa; Wada, Masatoshi
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Japanese Efforts to Promote Steel Reuse in Building Construction

Masanori Fujita¹, Tetsuya Fujita², Mamoru Iwata³, Yoshihiro Iwata⁴, Tomomi Kanemitsu⁵,
Urara Kimura⁶, Kazuhiko Koiwa⁷, Mitsumasa Midorikawa⁸, Taichiro Okazaki, M.ASCE⁹,
Satoshi Takahashi¹⁰, Teruhisa Tanaka¹¹, and Masatoshi Wada¹²

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

¹ Professor, Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa 221-8686, Japan. E-mail: fujitam1@kanagawa-u.ac.jp

² Senior Project Engineer, Nihon Sekkei Inc., Tokyo 163-1329, Japan. E-mail: fujita-t@nihonsekkei.co.jp

³ Professor Emeritus, Kanagawa University, Yokohama, Kanagawa 221-8686, Japan. E-mail: iwata@kanagawa-u.ac.jp

⁴ Senior Research Engineer, Building Research Institute, Tsukuba, Ibaraki 305-0802, Japan. E-mail: yiwata@kenken.go.jp

⁵ Chief Research Engineer, Shimizu Corporation, Tokyo 104-8370, Japan. E-mail: kanemitsu@shimz.co.jp

⁶ Chief, Japan Testing Center for Construction Materials, Tokyo, 103-0012, Japan. E-mail: u_kimura@jtccm.or.jp

⁷ Associate Director, Structural Engineering Department, Mitsubishi Jisho Sekkei Inc., Tokyo 100-0005, Japan. E-mail: kazuhiko.koiwa@mj-sekkei.com

⁸ President, Building Research Institute, Tsukuba, Ibaraki 305-0802, Japan. E-mail: midorim@kenken.go.jp

⁹ Professor, Faculty of Engineering, Hokkaido University, Sapporo, Hokkaido 060-8628, Japan. E-mail: tokazaki@eng.hokudai.ac.jp (corresponding author)

¹⁰ Chief, Kajima Corporation, Tokyo, 107-8502, Japan. E-mail: takahsat@kajima.com

¹¹ Assistant Professor, Faculty of Engineering, Fukuoka University, Fukuoka, Fukuoka, 814-0180, Japan. E-mail: sttanaka@fukuoka-u.ac.jp

¹² Group Manager, Nippon Steel Metal Products, Co., Ltd., Tokyo, 101-0021, Japan. E-mail: mwada@ns-kenzai.co.jp

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.

1 Introduction

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

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

20 Fig. 1 explains steel reuse in a circulation diagram. Circulation of structural steel may
21 be separated by the manufacturing processes and destination after the end of life of the structure.
22 Structural steel in Japan is produced by the blast furnace or electric furnace process. Although
23 there is no mandate to do so, many engineers specify blast-furnace steel for primary load-
24 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 m²) was relocated and reorganized into a new, slightly smaller gymnasium (total floor area 1,089 m²). 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 CO₂ emission associated with the steel framing system.

In Example 6, a factory (total floor area 1,059 m²) was relocated and reconstructed piece-by-piece into a new, nearly identical factory (total floor area 1,073 m²). 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 CO₂ 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/mm² 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 designed 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/mm². 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
628	1952 JIS G 3101 (SS steel)				1950 Calculation Standard for Steel Structures
629		1954 JIS G 3192			1950 BSL enforced
630	1952 JIS G 3106 (SM steel)				
631				1961 JIS G 3444 (STK)	1961 Specific block system introduced
632		1964 Production of jumbo sections			
633		1966 new sections added to JIS G 3192			
634			1966 JIS G 3466 (STKR)		
635			Late 1960's Production by formed-from-round process started		
636			Mid 1970's Production by form-square weld-square process started		
637					1981 Two-level design introduced
638					1970 Design Standard for Steel Structures
639					1975 Recommendations for the Plastic Design of Steel Structures
640					1980 Recommendations for Stability Design of Steel Structures
641		1989 Production of constant-depth sections			
642			1989 JSS II 10 (STKC R/P)		
643		1990 JIS G 3192 updated (web tolerance tightened)			
644	1991 MC-TMCP steel				
645		1994 JIS G 3192 updated (r-tolerance tightened)			
646	1994 JIS G 3136 (SN steel)				
647			1995 Ministry-approved BCR		
648			1995 Ministry-approved BCP		
649	1996 Ministry-approved Grade 590 steel			1996 JIS G 3475 (STKN)	
650					1998 Recommendation for Limit State Design of Steel Structures
651	2000 Ministry-approved LYP steel				1998 Performance-based design introduced
652		2005 JIS G 3192 updated (10 sections added 1 section removed)			
653		2008 JIS G 3192 updated (flange tolerance tightened)			
654	2009 Ministry-approved Grade 780 steel				2009 Manual for Re-using structural members
655		2014 JIS G 3192 updated (added universal-depth sections)			2013 Recommendation for Design of KIGEN-TSUKI Structures
656					2014 Recommended Provisions for Seismic Damping Systems applied to Steel Structures
657					2015 Recommendations for Sustainable Steel Building Construction (Draft) -Member Reuse-
658					
659					
660					
661	<u>Note:</u>	Japanese Industry Standards (JIS)			
662		JIS G 3101	Rolled steels for general structure	JIS G 3106	Rolled steels for welded structure
663		JIS G 3136	Rolled steels for building structure	JIS G 3192	Dimensions, mass and permissible variations of hot rolled steel sections
664		JIS G 3444	Carbon steel tubes for general structure	JIS G 3466	Carbon steel square and rectangular tubes for general structure
665		JIS G 3475	Carbon steel tubes for building structure		
666		Standard of Japanese Society of Steel Construction (JSS)			
667		JSS II 10	Cold formed rectangular hollow section steel columns		

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

Designation	Tensile Requirements				Chemical Requirements				
	Yield Strength	Tensile Strength	Yield-to-Tensile	Elongation	C	Si	Mn	P	S
	[N/mm ²]	[N/mm ²]	Ratio [%]	[%]	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

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

673 **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

674

675 **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	

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

677

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679 Fig. 1 Circulation of structural steel.

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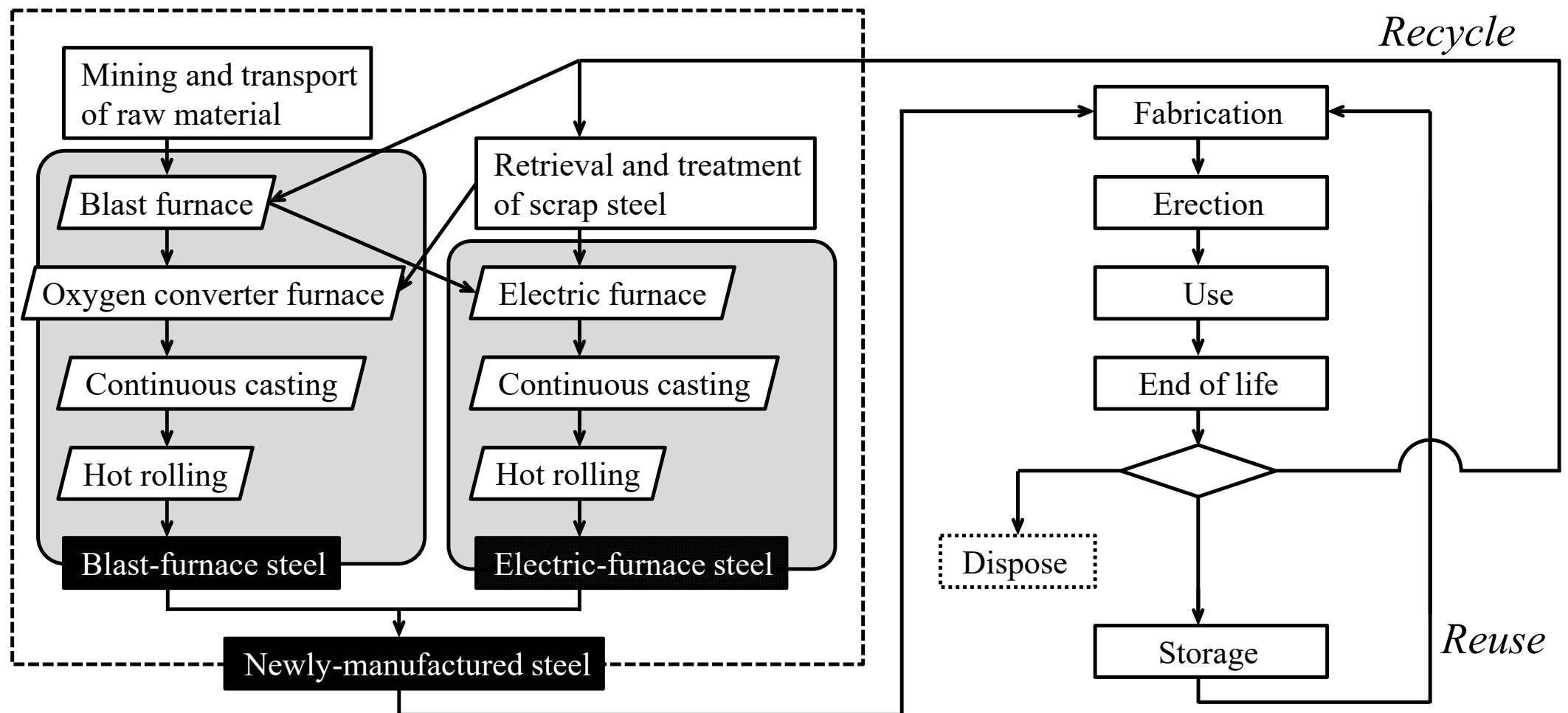


Fig. 1 Circulation of structural steel.



(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)

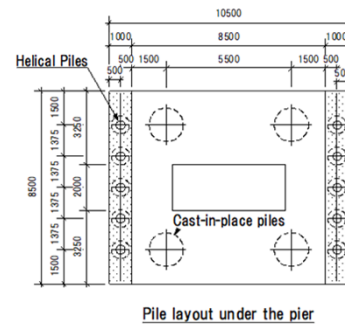
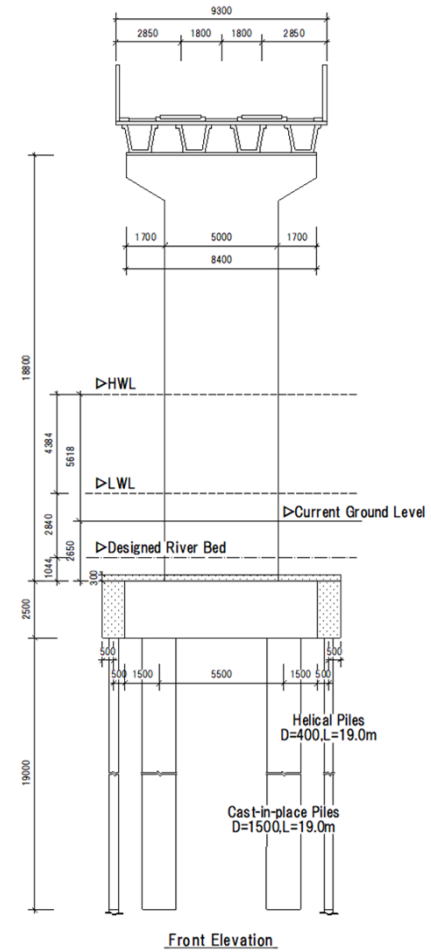


(b)

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]).

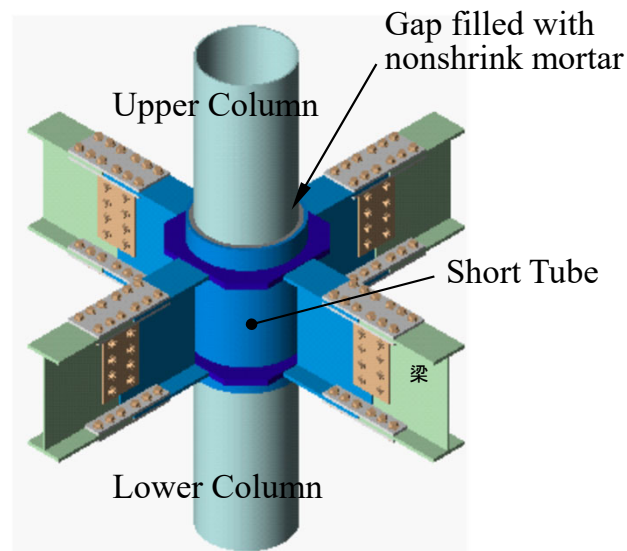


Fig. 6 Composition of detachable connection.



(a)



(b)

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

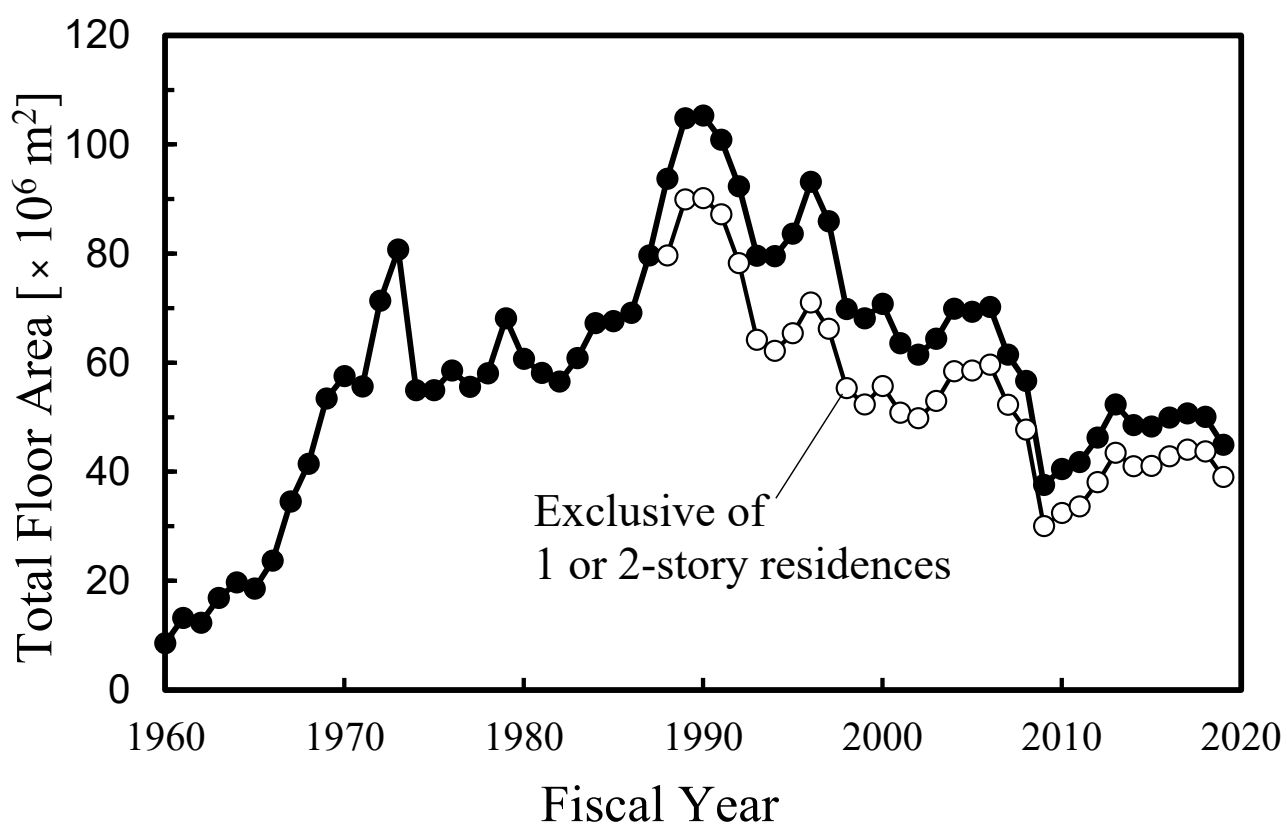


Fig. 8 Steel building construction since 1960 in terms of floor area (Produced from data by MLIT, 2021).

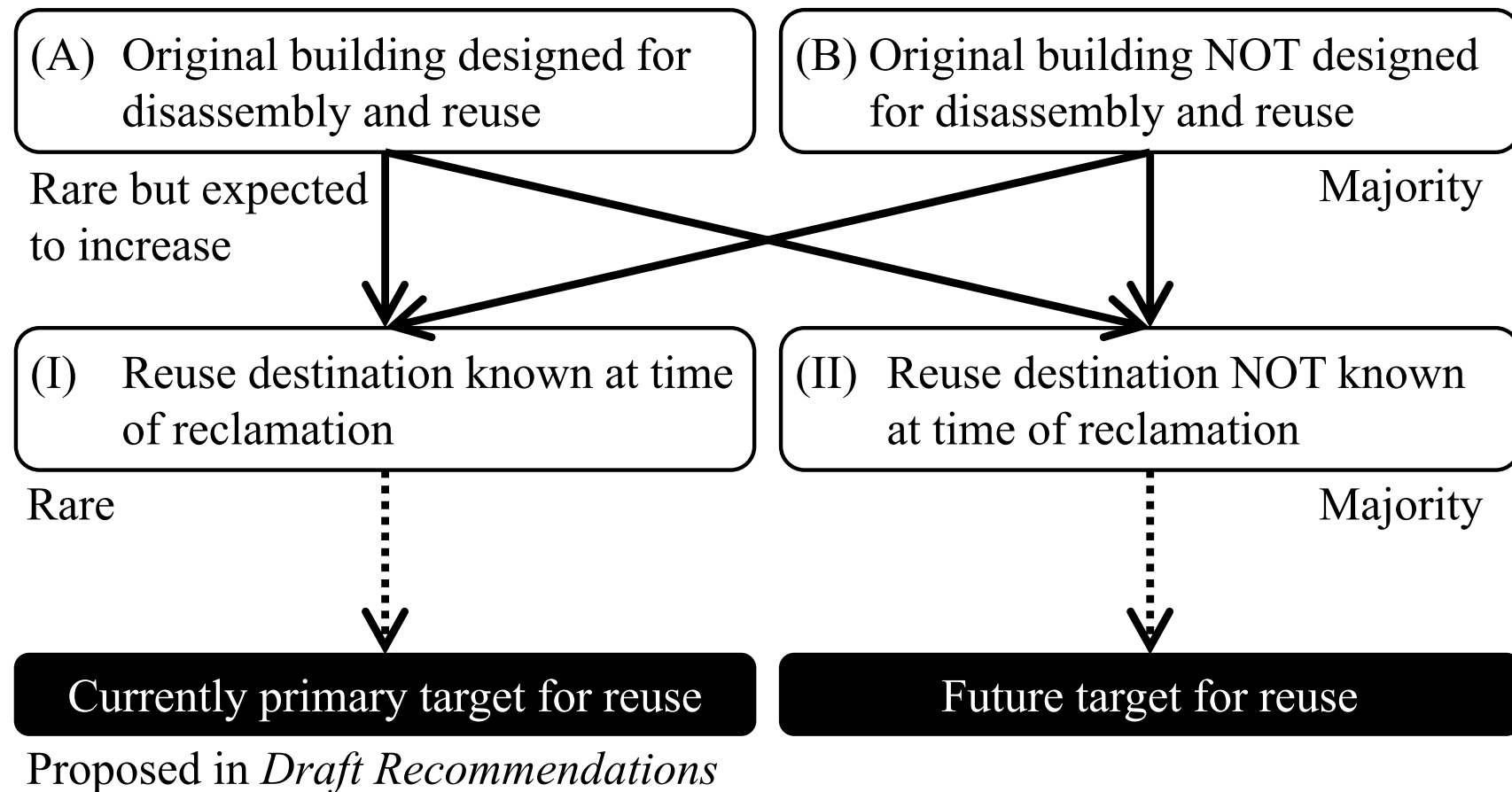


Fig. 9 Categories of steel reuse projects.

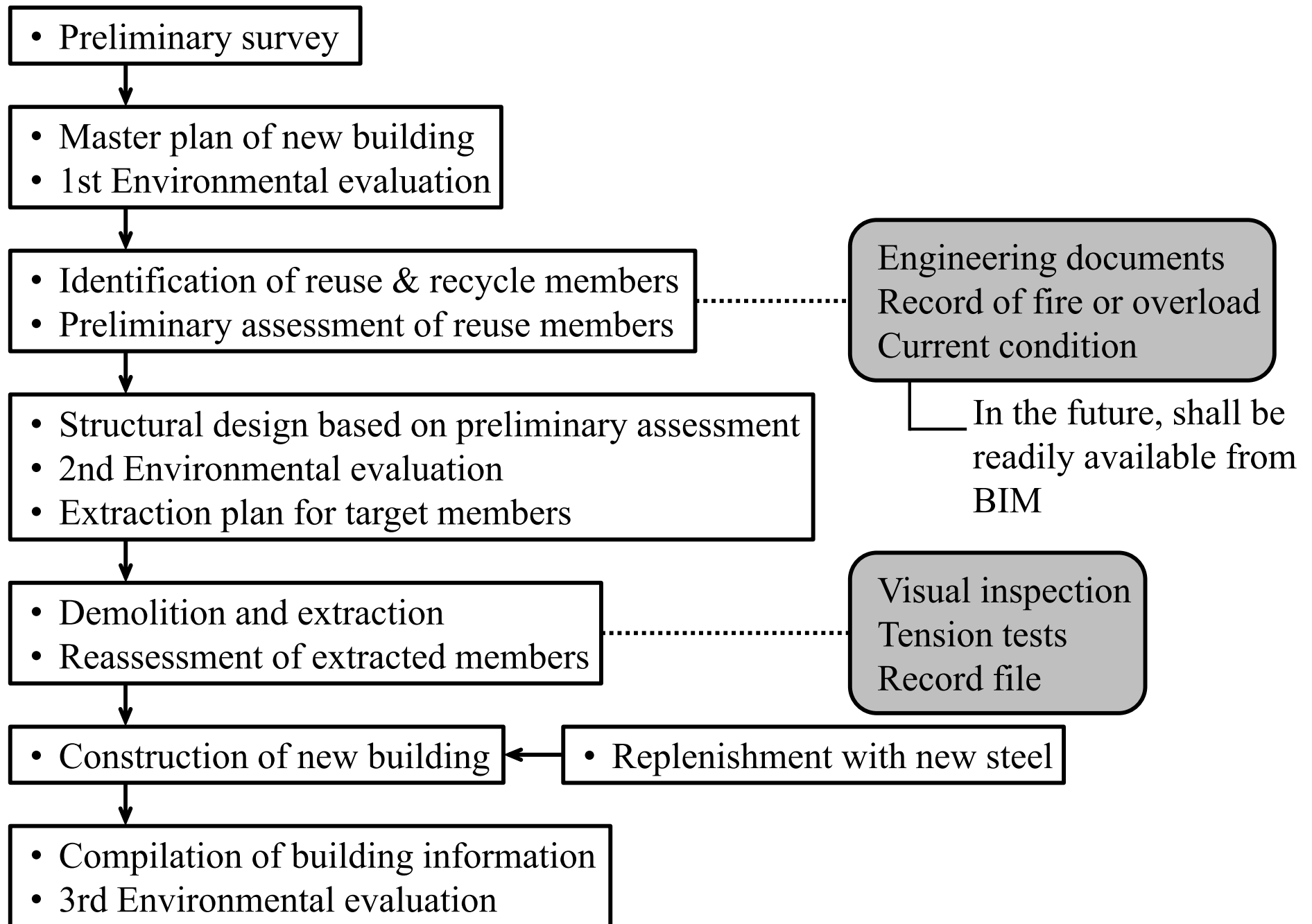


Fig. 10 Engineering procedure for steel reuse.

**(1) Preliminary Survey and
1st Environmental Evaluation**

- Master plan
- 1st Environmental evaluation

**(2) Structural Design and
2nd Environmental Evaluation**

- Preliminary assessment

- 1st Environmental evaluation

- Structural design

- 2nd Environmental evaluation

(3) Extraction and Reassessment

- Extraction

- Reassessment of extracted members

(4) Construction

(5) Record Keeping and 3rd Environmental Evaluation

- Compilation of building information
- 3rd Environmental evaluation

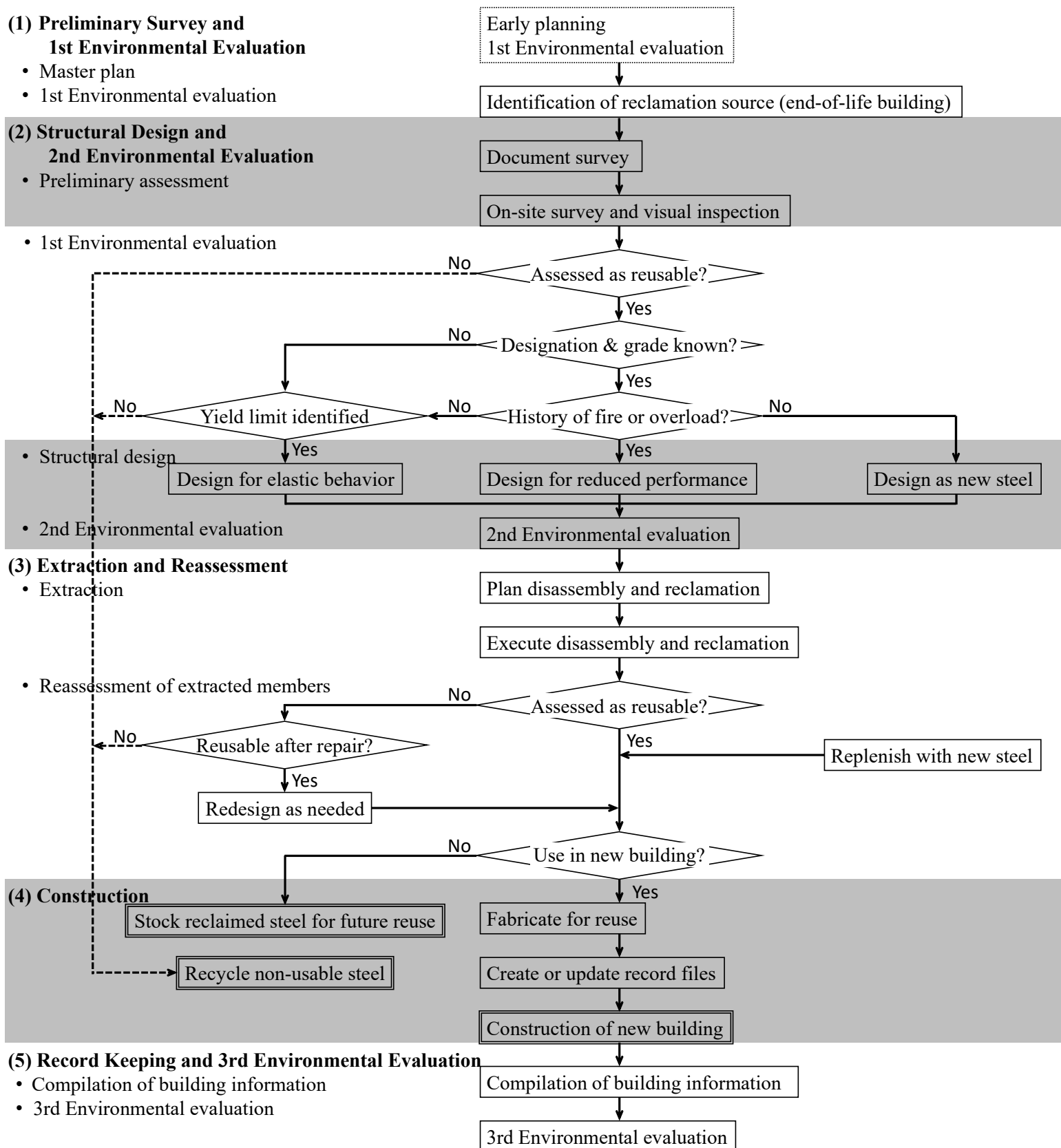


Fig. 11 Engineering procedure when the destination of reclaimed steel is predetermined.