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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.

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

25 and maintenance during use, and end of life. At the end of life of the building, the steel may be
26 reused, recycled to produce newly manufactured steel, or disposed. In Japan, nearly all steel is
27 recycled. Reuse, which is the most ideal option to serve sustainable development, is prevented
28 by a number of barriers. The barriers described in the literature (e.g., Addis 2006; Dunant et al.
29 2017; Tingley et al. 2017; Hopkinson et al. 2019), such as lack of interest, confidence in the
30 retrieved steel, supply, integrated guidance, among other factors apply to Japan.

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

47 In the rest of the paper, the state-of-art of steel reuse in Japan is discussed from
48 motivation, relationship with seismic design requirements, technology that aid reuse, material
49 properties, reuse projects, to a proposed design procedure, and future directions. A key notion

50 to the discussion is that, unlike many other parts of the world (Brown et al. 2019), buildings in
51 Japan cannot escape the possibility of experiencing an earthquake within its lifetime.

52 Motivation: Why Reuse Steel?

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

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

74 assessment tools include a category for rewarding green material, for which reused steel
75 qualifies.

76 Technology for Disassembly

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

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

98 easy disassembly. Similar systems are being developed around the world, for example by
99 Mansour (2011).

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

102 *Helical piles*

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

111 An important benefit of helical piles is relative ease in removal. As illustrated in Fig.
112 4, removal is conducted by (1) exposing the pile cap, (2) killing the friction resistance between
113 the pile body and soil by repeating forward and reverse rotation, then (3) introducing reverse
114 rotation to pull out the pile, and, as needed, (4) gas cutting to length adequate for transportation.
115 The removed pile may be reused after adequate inspection (visual, dimension measurement,
116 mechanical properties) and refurbishing.

117 Two-thousand helical piles, 114 to 600-mm in diameter, were removed after the Expo
118 2005 in Aichi, Japan, although unfortunately those piles were disposed before being reused.
119 Reuse of helical piles has been reported from a rapid restoration project of railroad bridge piers
120 tilted after by the 2011 Tohoku earthquake (Iwamoto and Yonezawa 2012). In this project, as
121 indicated in Fig. 5a, 400-mm diameter helical piles were used in temporary reaction systems to

122 jack the piers back to vertical. These piles were subsequently removed, refurbished, and
123 afterwards reused for strengthening the foundations of the same piers, as shown in Fig. 5b.

124 *Detachable connections for automated construction*

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

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

138 **Properties of Structural Steel in the Building Stock**

139 The building stock in Japan was constructed over the last sixty years. As seen in Fig.
140 8, steel is a common construction material today, but very few steel buildings were constructed
141 prior to 1960. Buildings in Japan may be separated into two eras by structural design
142 requirements: before or after the 1981 amendment of the Building Standard Law. Before the
143 amendment, buildings were designed based on allowable stress requirements. The amended
144 Building Standard Law requires building structures to satisfy two levels of seismic

145 requirements: Level 1 intends to assure that the structural system remains largely undamaged
146 during moderate earthquakes, while Level 2 intends to prevent structural collapse and thereby
147 assure life safety during severe earthquakes (IIBH 2021). Level-1 design calls for allowable
148 stress checks, with a safety factor of unity, against seismic loads typically computed for a base
149 shear coefficient of 0.2. Level-2 design calls for nonlinear analysis against a base shear
150 coefficient of 0.25 to 0.5, depending on the ductility category of system. Historically, Japanese
151 research was influenced by the U.S., as evidenced by the fact that AIJ publications referred to
152 American Institute of Steel Construction (AISC) specifications at the time but modified to meet
153 high seismic demands.

154 Table 1 summarizes the historical development of structural steels and relevant codes
155 and provisions in Japan. Production of structural shapes started in the mid-1950's. The first
156 Japanese Industrial Standard (JIS) on mechanical and chemical requirements for structural steel
157 was established in 1952. The most common steel was SS and SM steel until SN steel was
158 introduced in 1994. Since the 1990's, a wide array of structural steel has been introduced in the
159 market, although the high-strength variety and low-yield-point steel have not been included in
160 JIS but recognized as material certified by the Minister of Land, Infrastructure, Transport and
161 Tourism (hereinafter referred to as Minister-certified material). Minister certification is a
162 product-by-product, factory-by-factory process to permit use of non-JIS material in building
163 construction. The JIS dimensions and geometric requirements, first established in 1954, has
164 been updated to tighten the dimension tolerance and to introduce a very large number of
165 "universal-depth" beam sections (with universal d dimension rather than universal h).
166 Production of square hollow structural sections (HSS) started in the late 1960's. Square HSS
167 produced from SS or SM steel by the formed-from-round process and form-square weld-square
168 process were recognized in 1989 by the Standard of Japanese Society of Steel Construction
169 (JSSC) Standard JSS II 10 as STKC R and P, respectively. More recently, square HSS are

170 produced predominantly from SN steel and are recognized as Minister-certified material, BCR
171 and BCP. Today, BCR is available in sizes up to $h = b = 550$ mm, while BCP is available to $h =$
172 $b = 1,400$ mm. Larger and heavier columns are built up by combining four steel plates with
173 complete-joint-penetration groove welds using a submerged-arc welding process. Since the
174 1990's, square columns produced by either of the three methods have taken over I-section
175 columns. Over the last three decades, the fabrication and construction methods have remained
176 largely unchanged except for the improvements in connection details after the 1995 Kobe
177 earthquake and increasing tendency in structural design to adopt tighter drift limits to control
178 nonstructural damage during seismic events.

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

187 Table 3 summarizes statistical data collected from mill test reports, available from
188 three different periods, reported by Aoki and Murata (1984), Shimura et al. (2003), and
189 Fujisawa et al. (2013). The average values over a range of plate thickness and shapes are listed.
190 The slight decrease in mean strengths and coefficient of variations (COVs) may be a result of
191 improvement in manufacturing technology. However, the change over a span of 30 years is
192 negligible for the engineering practice. In many regards, the average steel produced in the
193 1980's meets the current JIS specification for the same strength grade.

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

200 Examples of Reuse

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

218 In Example 5, a gymnasium (total floor area 1,483 m²) was relocated and reorganized
219 into a new, slightly smaller gymnasium (total floor area 1,089 m²). The new gymnasium was
220 constructed from steel members and external finish reclaimed from the original gymnasium.
221 Although data from mill test reports were lost, member reuse was approved by authority based
222 on evidence of steel grade provided in engineering drawings and calculation records of the
223 original building. The original building had not been exposed to fire or major earthquake. After
224 careful disassembly, each member was visually inspected. It is estimated that the use of
225 reclaimed steel over newly manufactured steel for the new gymnasium resulted in 97% or 180-
226 t reduction in CO₂ emission associated with the steel framing system.

227 In Example 6, a factory (total floor area 1,059 m²) was relocated and reconstructed
228 piece-by-piece into a new, nearly identical factory (total floor area 1,073 m²). Approval by
229 authority was done similarly to Example 4. Because both buildings were near the shore,
230 members reclaimed from the original building were transported to the construction site by
231 barges. After visual inspection, the members were used with minimal repair and alteration. The
232 estimated CO₂ reduction associated with the steel framing system is estimated as 96%.

233 Design Methodology

234 *Different Possibilities of Steel Reuse*

235 Steel reuse may be categorized into the possibilities illustrated in Fig. 9. The source of
236 member reclamation, i.e., the original building, may be: (A) a building designed for disassembly
237 and reuse; or (B) a building not designed for disassembly and reuse. Examples of (A) are rare
238 but have existed in association with special events such as world expos and international sport
239 events. Case (A) is not unusual for temporary structures with predetermined life. Nonetheless,
240 (B) is the norm for the vast majority of buildings. Considering the fact that, in Japan, the life
241 span for commercial buildings in big cities can be as short as 15 years, and a big proportion of

242 the building stock constructed in the 1970' to 1990's (see Fig. 8) is expected to be replaced in
243 the near future, (B) should be recognized as the primary target.

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

250 *Design for Deconstruction and Reuse*

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

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

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

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

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

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

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

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

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

290 Fig. 10 summarizes the engineering process for such cases. While Hradil et al. (2021)
291 present an engineering process specialized for single-story steel buildings, the scope of Fig.
292 10 is applicable for general steel buildings, from single-story buildings to multi-story office
293 buildings. At the planning stage, access to members targeted for reuse may be limited because
294 the building is in use, and/or the members are shielded by architectural finish and fire
295 proofing. The preliminary assessment on reusability shall be based on document review and
296 visual inspection, and therefore, expected to be no more than a presumption. Therefore, a
297 second, more thorough assessment shall be made after the members are extracted.

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

304 (1) Preliminary Survey and First Environmental Evaluation

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

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

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

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

324 (2) Structural Design and Second Environmental Evaluation

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

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

336 (3) Reclamation and Reassessment

337 Appropriate disassembly shall be conducted to extract the target members efficiently

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

344 (4) Construction

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

350 (5) Data Management and Third Environmental Evaluation

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

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

360 The above-described procedure was, in general, followed in the reuse examples listed
361 in Table 4. In all examples, the original building had no history of fire or overload, reclaimed

362 members were reused in the primary load-resisting system, careful disassembly was conducted
363 to extract the targeted members damage free, and an environmental evaluation was conducted
364 either at the start and/or end of the project. Therefore, the proposed procedure should be directly
365 applicable to the current Japanese practice, and it could be understood as a clarification of what
366 should be done to achieve a successful reuse project.

367 Future Directions

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

370 (1) *Establish a procedure to quantify the remaining structural performance of degraded*
371 *steel*

372 (2) *Establish connections designed for disassembly*

373 (3) *Incorporate member reuse in green building certification*

374 (4) *Introduce modularized structural systems*

375 (5) *Establish a commercially feasible market*

376 (6) *Secure traceability of steel*

377 The six items have been discussed extensively in the literature. Item (5) has been identified as
378 the most significant barrier by many studies (Addis 2006; Dunant et al. 2017; Tingley et al.
379 2017; Hopkinson et al. 2019). Item (2) is addressed by research to develop deconstructable
380 and reusable composite slabs (Gritsenko et al. 2019; Jakovljević et al. 2020), and proposed
381 connections that minimize welds and rely instead on bolts (Hradil et al. 2021). Item (3) is
382 discussed extensively by Pongiglione and Calderini (2015). Item (4) is recognized by Pulaski
383 et al. (2004) and ISO (2004). Item (6) is emphasized by Hradil et al. (2014), Brown et al.

384 (2021) and ISO (2020). The following discussion emphasizes the significance of each item
385 and associated challenges for Japanese construction.

386 *(1) Establish a procedure to quantify the remaining structural performance of degraded steel:*

387 If convincing evidence is available to prove that a member reclaimed from an older building
388 possesses the same mechanical properties as newly manufactured steel, then the member may
389 be used similarly as new steel. If no authentic record, in form of mill test report or record file
390 as described later, is available, then the reclaimed member may be limited for use in the
391 elastic domain as floor beams or other secondary members. A conservative estimate shall be
392 used for their yield strength: In Japan, 235 N/mm² shall be adequate because this has been the
393 minimum specified yield strength since the establishment of JIS. If imperfection beyond
394 tolerance, whitening by fire, or substantial area loss due to rust is detected by visual
395 inspection, then the reclaimed member is not suited for reuse and therefore should be
396 recycled.

397 However, there is a lack of scientific evidence to judge the appropriate use of
398 reclaimed members that may be degraded. Research is needed to understand the change in
399 mechanical properties over life cycle, due to fabrication, construction, reclamation as well as
400 condition of use. The *Draft Recommendations* propose a concept of using reduction factors to
401 address degradation in strength and ductility but falls short of providing specific values for the
402 factors. The causes of degradation include: (a) post-yield deformation due to overload or
403 seismic effects combined with strain aging; (b) fatigue due to large number of stress cycles;
404 (c) fire; (d) corrosion; (e) weld; (f) plastic work introduced during manufacturing (forming)
405 and fabrication (cambering); and (g) thermal loading cycles. The degradation caused by each
406 of these causes must be quantified before the reduction factors mentioned above may be
407 established. Among the seven causes, (a) is believed to be by far the most significant for
408 Japan: Steel members in Japan experience earthquakes with high likelihood during use

409 because the entire country is in high-seismicity region, and steel construction tends to adopt
410 full moment frames where all primary members participate in lateral load resistance. A
411 measure is needed to quantify the remaining seismic performance of steel members based on
412 evidence such as residual story drift, residual member deformation, and visual appearance.

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

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

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

437 *(4) Develop structural systems that are suited for member reuse:* For many years, reuse has
438 been common in the construction industry for shoring, scaffolding, temporary stadium
439 seating, event tents, and other short-term facilities. These structures are composed of
440 members of limited types and dimensions. Take for example shoring for ground excavation:
441 the Japanese industry uses I-sections with $h = b = 200$ to 500 mm, with H-350×350×10×15
442 and H-350×350×12×19 being by far the most widely circulated. As mentioned for Examples
443 3 and 4 in Table 4, the prefabricated house manufacturers have established a scheme to
444 circulate their standardized cube-framed steel units after repair and refurbishment. Similarly,
445 the potential sources of reclaimed steel and their consumers may be maximized by further
446 standardizing, or modularizing steel buildings. Features required for reusable members are:
447 standardized dimensions, longer rather than shorter length, I-sections as opposed to tubular
448 sections, minimal attachments, holes or stiffeners. It is acknowledged that, unfortunately, the
449 Japanese construction industry has been moving in the exact opposite direction to these
450 requirements. A breakthrough idea that does not conflict with the current norm of the
451 construction industry is needed.

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

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

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

475 Summary

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

- 478 1. Although strong interest in steel reuse has been shared by the government, industry and
479 research community, very few reuse projects have been realized to date. The AIJ is taking
480 a leadership role to make steel reuse a wide-accepted reality in Japan.
- 481 2. Steel construction became common in the 1960's. Since that time, the minimum specified

482 strength of the lowest grade steel has always been 235 N/mm². Little change in mean and
483 coefficient of variation is seen since the 1980's. Control of weldability and yield-to-
484 tensile ratio has improved over years, especially due to the introduction of SN steel in
485 1994.

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

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

495 Data Availability Statement

496 All data, models, and code generated or used during the study appear in the published
497 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	Note:	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				

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

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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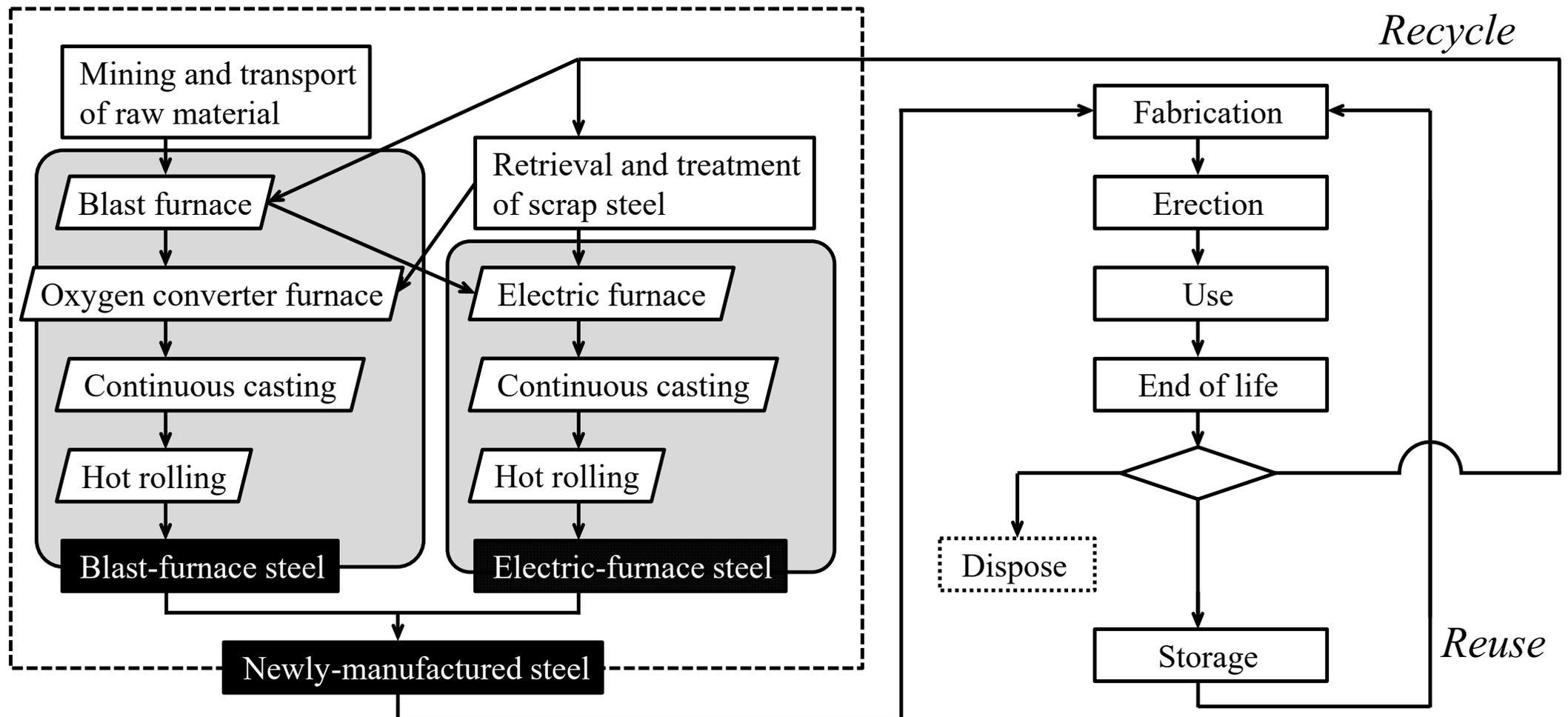


Fig. 1 Circulation of structural steel.



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)

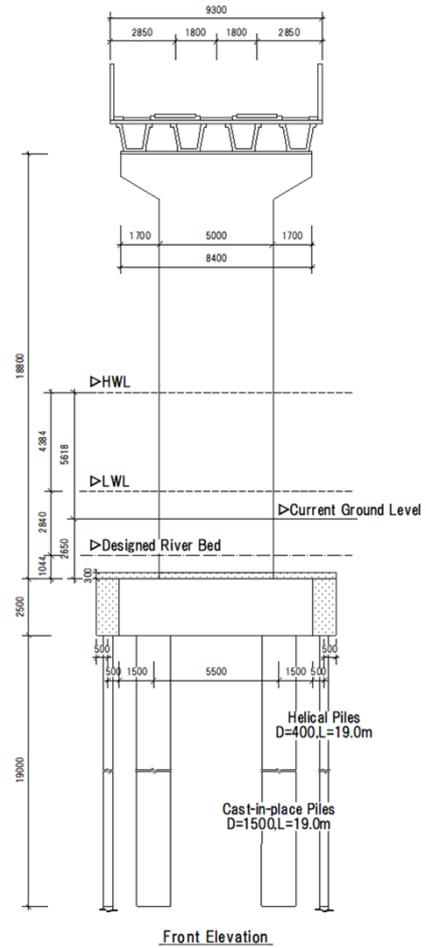


(b)

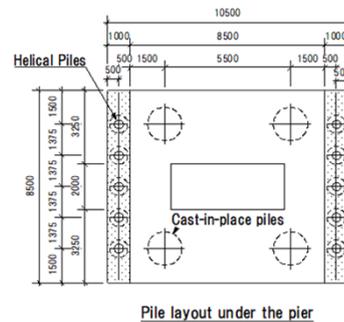
Fig. 4 Removal procedure of 900 to 1100 mm-diameter helical piles: (a) operation; and (b) steel blade in sound condition after removal. (Courtesy of Association of NS ECO-PILE method).



(a)



Front Elevation



Pile layout under the pier

(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]).

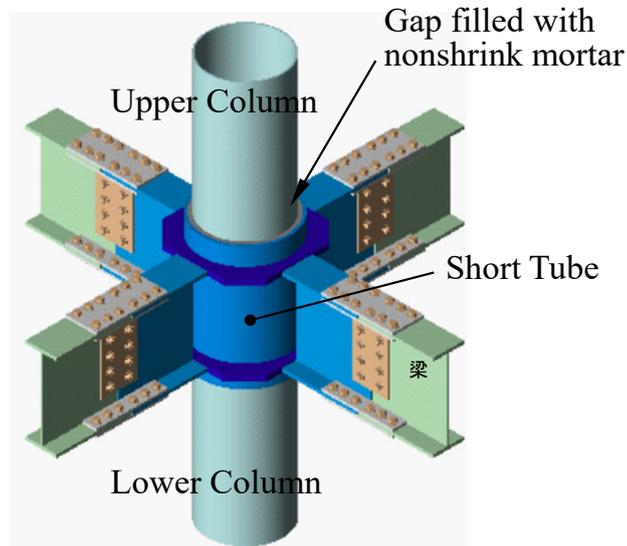


Fig. 6 Composition of detachable connection.



(a)



(b)

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

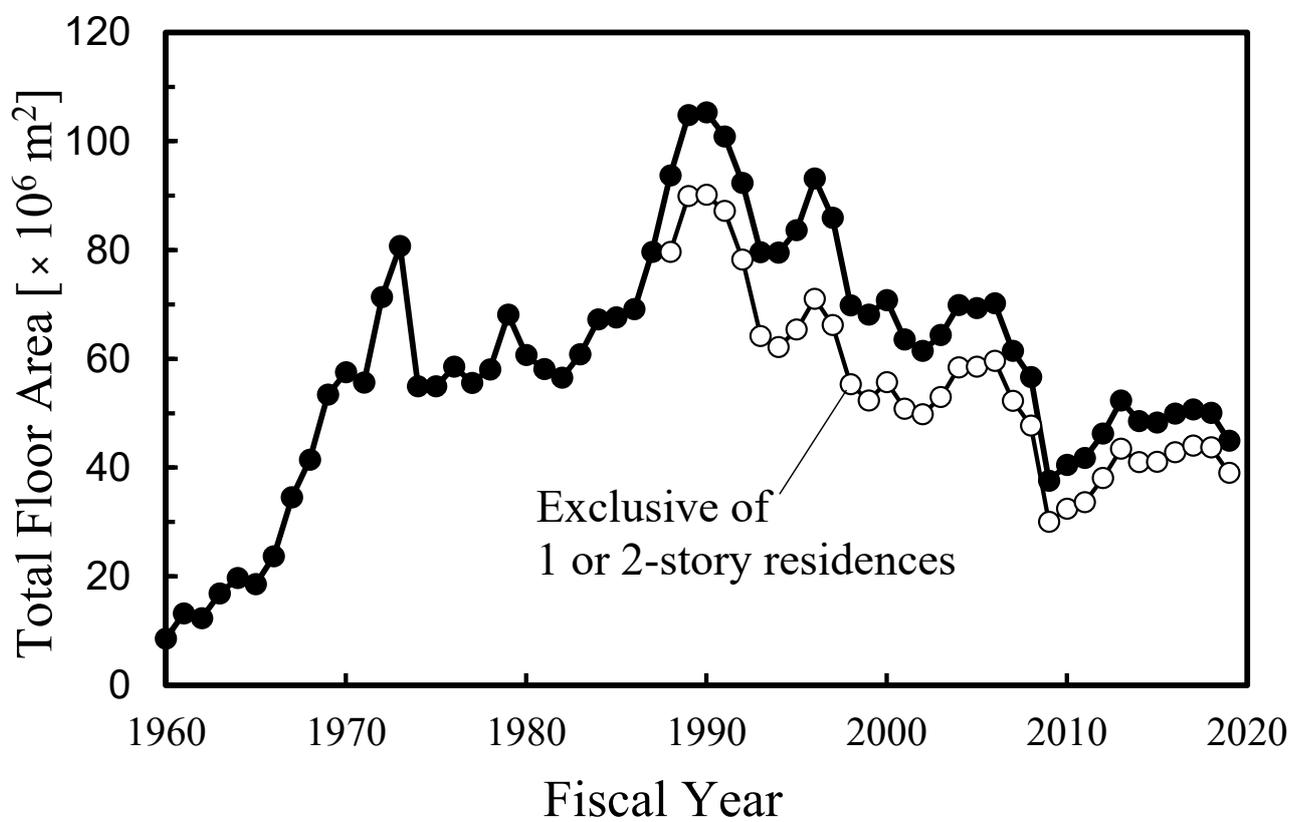


Fig. 8 Steel building construction since 1960 in terms of floor area (Produced from data by MLIT, 2021).

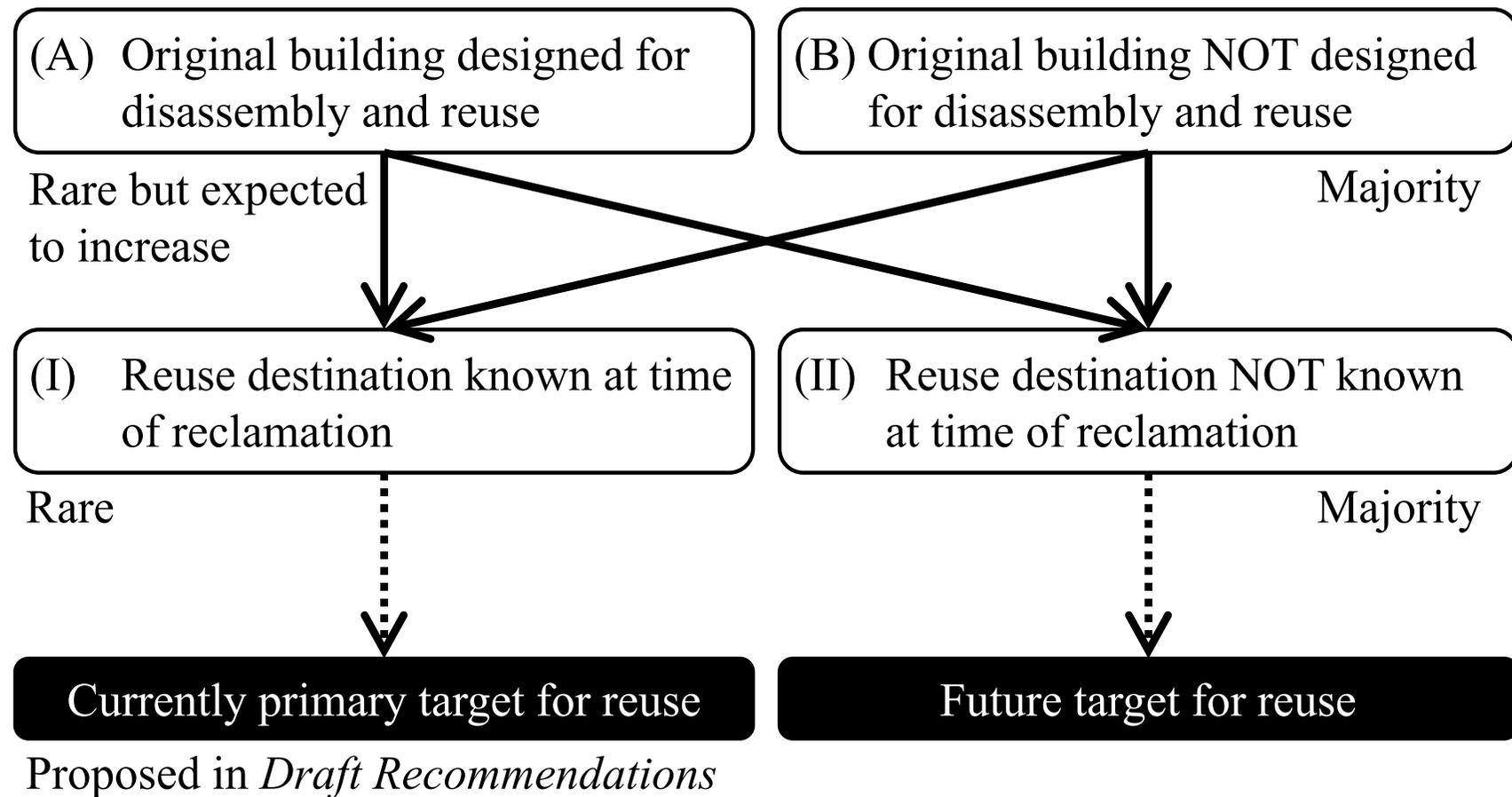


Fig. 9 Categories of steel reuse projects.

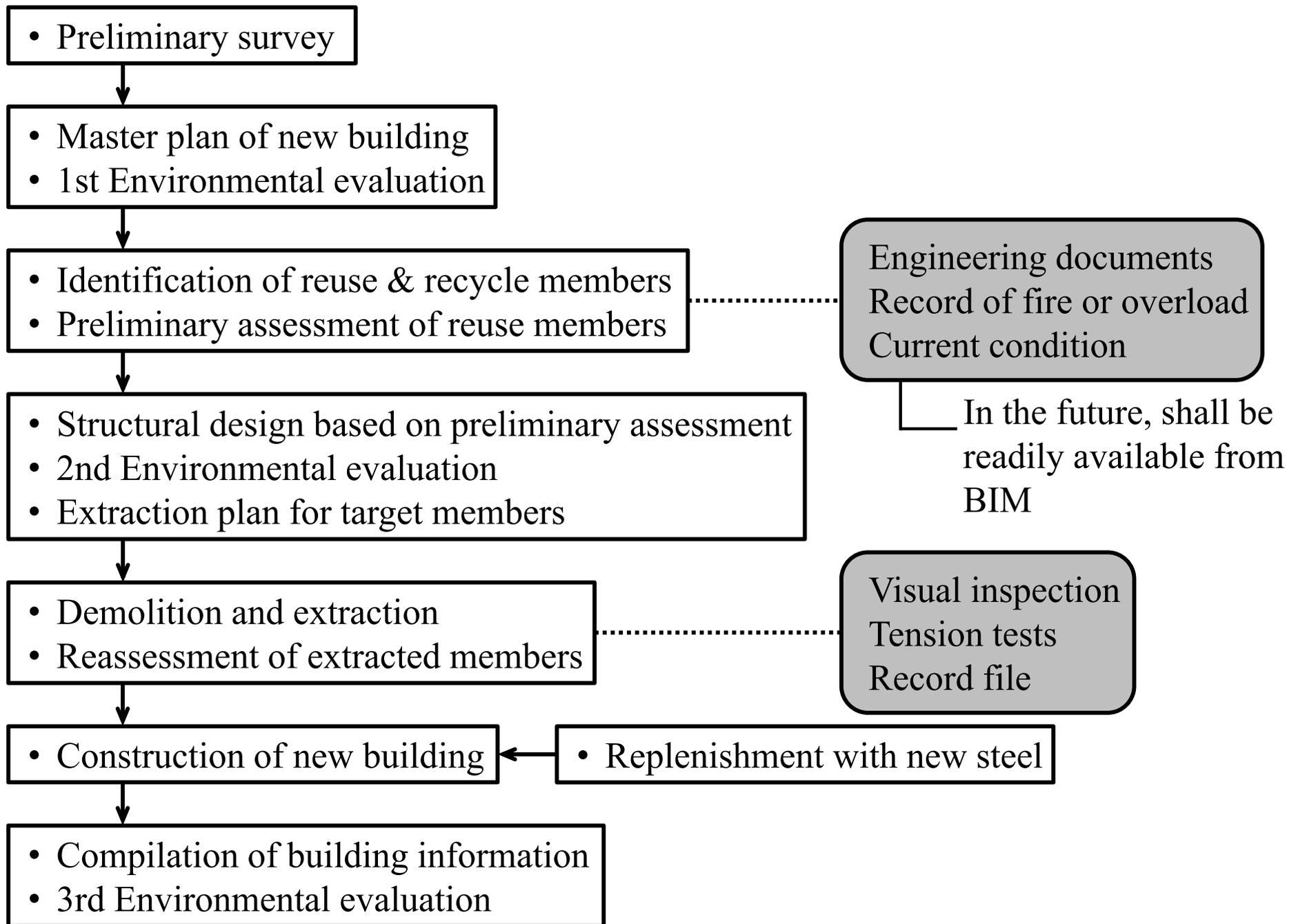


Fig. 10 Engineering procedure for steel reuse.

(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

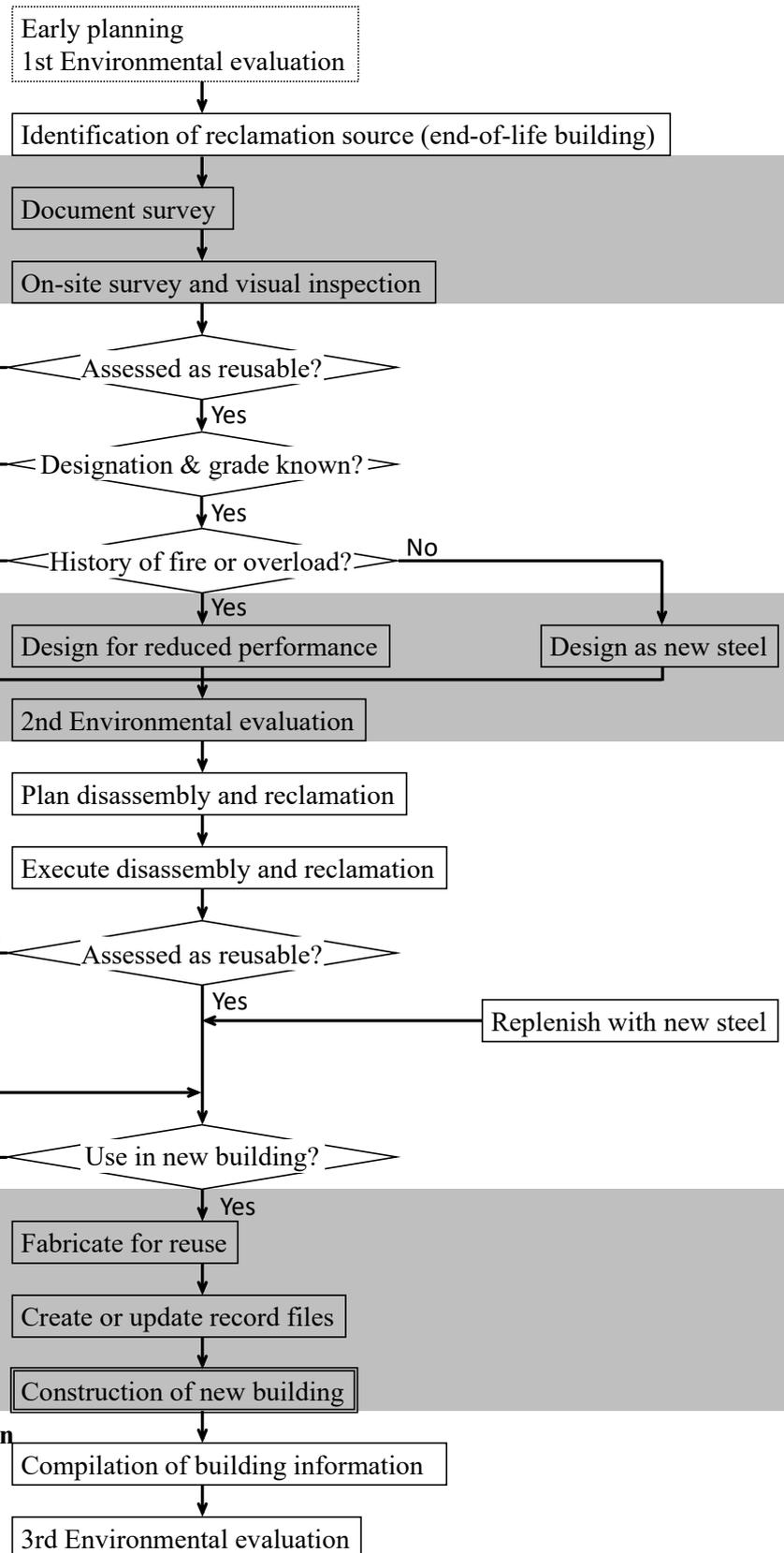


Fig. 11 Engineering procedure when the destination of reclaimed steel is predetermined.