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ReCreate

Reusing precast concrete for a circular economy

Räsänen et al.

Procedure for quality management of reclaimed concrete elements

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Abstract

A quality management procedure for ensuring the safe reusability of deconstructed precast concrete elements is essential for more widespread and mainstreamed reuse. The quality of reclaimed elements should be maintained throughout the process, and any reductions thereof that may have occurred must be reliably identified.

The ReCreate project researches reusing precast concrete elements, not originally designed for disassembly, through real-life deconstruction and reuse pilots in four European countries. The project covers all essential aspects of the whole reuse process, including quality management.

For reuse to be safe and to have potential for business profitability, the quality and value of precast concrete elements must be consciously managed throughout different process phases. Reusability in high-value applications can be ensured with the help of a systematic quality management procedure, which has dedicated stages for the different phases of the overall reuse process. The quality of the elements can be inadvertently reduced in each stage, and thus the possible reducing factors need to be considered individually.

This document presents the initial outline for the quality management procedure under development in the project. The key process stages are:

- Pre-deconstruction audit, where the main actions are finding out the type and number of elements, assessing their reuse potential, and gathering information for the next stages.
- Structural investigation, where the main actions are ensuring material properties of elements primarily with non-destructive (ND) or semi-destructive (SD) methods, determining the condition of the elements, and finding out the existence of possible hazardous substances.
- Deconstruction design and execution, where the determination of safe deconstruction and lifting methods is the main action, together with transportation and storage of deconstructed elements.
- Full-scale testing is carried out if the structural capacity of reclaimed elements cannot be uncovered through other means or if there is doubt about safety factors. Also newly developed retrofit connections need testing if original connections cannot be reused.
- Redesign and reassembly, where the main actions are designing the reclaimed elements according to Eurocodes and standards in force. Also, the refurbishment of the reclaimed elements must be designed.
- Product approval and authorisation is the final stage, where documents from the previous stages, together with technical drawings and calculations, will be presented to authorities to obtain official permits for reuse.

Visual investigation and thorough documentation are an essential part of each stage. Information must be carried through from stage to stage.

The current report presents the key process stages, along with a discussion on factors that may reduce the quality of salvaged elements and which must thus be addressed. By the end of the project, this outline will be developed into a best practice proposal, which will be published as a separate deliverable.

Acknowledgements

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Contents

Glossary

BIM	Building Information Model(ling)
BTU	Brandenburg University of Technology Cottbus-Senftenberg
CE	Conformité Européenne
CDE	Common Data Environment
CPR	Construction Products Regulation
D	Deliverable
EoW	End of Waste
ETA	European Technical Assessment
FD	Fully destructive
KTH	Royal Institute of Technology
LIDAR	Light detection and ranging
ND	Non-destructive
NFC	Near-Field Communication
PCI	Prestressed Concrete Institute
QR	Quick Response
RC	Reinforced concrete
RFID	Radion Frequency Identification
SD	Semi-destructive
TAU	Tampere University
TNO	Dutch Organization for Applied Scientific Research
TU/e	Eindhoven University of Technology
VOC	Volatile organic compounds
WP	Work Package

1. Introduction

The ReCreate project studies the reusability of precast concrete elements, not originally designed for disassembly, with the help of real-life deconstruction and reuse pilot projects located in Finland, Sweden, the Netherlands, and Germany. An interested reader finds a description of the deconstruction pilots in Vullings et al. (2024a), while details on the reuse pilots will be reported on in a future deliverable. The purpose of the current publication is to focus on the quality management process of such elements: which stages it consists of, and what needs to be considered in each stage.

The main purpose of the quality management process of reclaimed elements is to ensure the material properties and physical condition of the reclaimed elements, which in turn help to ensure the structural properties and structural safety of the reused elements in a new building. This is important, as the properties of materials and the physical condition of elements may decrease over time if they are subjected to stresses. If the properties, condition and capacity of elements are not known with sufficient reliability, reuse in the same purpose is not possible. Such downgrading to structurally less demanding applications leads to loss of potential economic value. In addition, the lack of established practices throughout the salvage and reuse process can lead to inadvertent changes in the quality of the elements. Therefore, a systematic process for the quality management is needed to verify unknown properties, to avoid any occurrences of inadvertent damage, and to so preserve the quality and economic value potential of salvaged elements. Such a well-delineated quality management process will also contribute significantly to the acceptance of reused precast concrete elements in building practice and to the normatively required substantiation of the structural safety of structures when building with reused concrete elements.

The quality management process is a vast subject, and it is virtually impossible to consider all possible aspects as detailed action suggestions for different cases. Therefore, the intention of the current document is to describe the process in general, and actions that should be considered while planning the quality management process for reuse of precast concrete elements in any individual case. The report is underlain by a variety of laboratory and field tests conducted as a part of ReCreate's real-life pilots before and after deconstruction, detailed in Räsänen et al. (2024). The project's recommendations for a best practice in quality management, including numbers of tests and samples, will follow in a future ReCreate deliverable D4.3.

2. Quality management process

The quality management process for reuse of precast concrete elements is divided into six main stages (Figure 1), which are: (1) pre-deconstruction audit, (2) structural investigation, (3) deconstruction design and execution, (4) full-scale testing, (5) redesign and reassembly, and (6) product approval and authorisation. Visual inspection and documentation are an essential part of each stage. The stages can be regarded as action modules to be followed. The nature and extent of the actions in the stages can vary, but the base structure is always present. Next, the contents of the stages are discussed in outline.

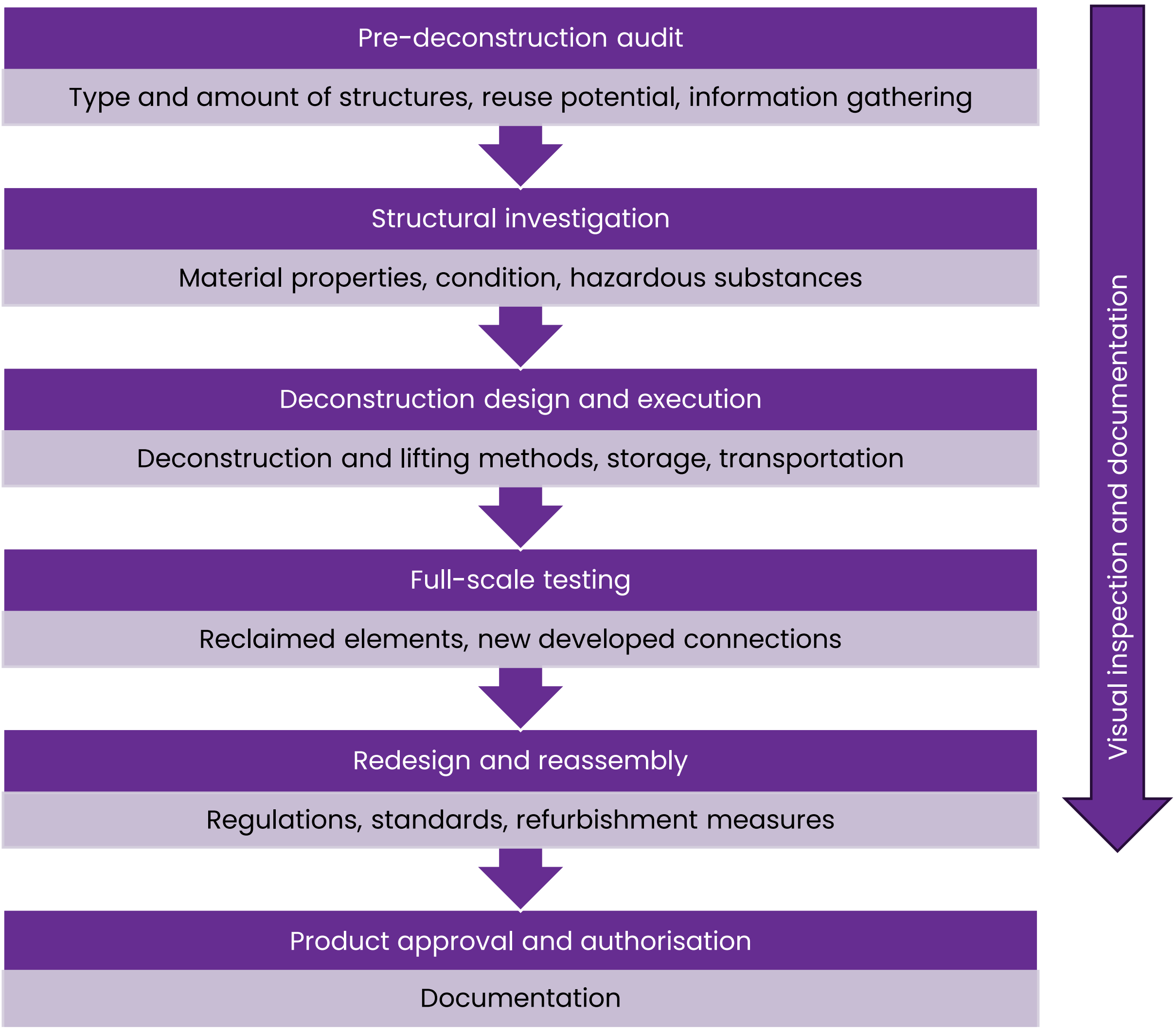

Figure 1. Action modules of the quality management process.

2. 1. Pre-deconstruction audit

The pre-deconstruction audit is an essential part of the quality management in that it contributes to two key aspects. Firstly, it helps to select good candidates for donor buildings, i.e. buildings that have prerequisites for deconstruction and element reuse. This sets the scene for achieving high quality throughout the process. Secondly, by gathering relevant information about the building, the pre-deconstruction audit lays the foundations for the subsequent stages of the quality management process.

The audit is carried out after the decision to decommission the building has been made and as it must be determined whether it will be deconstructed and its structural concrete elements reused, or if it will be demolished and its materials recycled. To make such a determination, information is required. The following considerations may inform the decision-making:

- **The type of the decommissioning**, whether full or partial. In some regions, such as Eastern parts of Germany, buildings are sometimes downsized, i.e. partially deconstructed, for urban redevelopment reasons. Such projects naturally lend themselves well to element salvage because the retention of the existing structure calls for delicate removal of the decommissioned parts of the building. On the other hand, the number of elements available for deconstruction may be smaller than in fully decommissioned buildings, potentially influencing the business viability of deconstruction and reuse.
- **The age of the building** may give some indication of its reuse potential. Since precasting was mainstreamed in the post-WWII era, if a concrete structure is older than that, it is most likely in-situ cast. Moreover, concrete precasting developed over the decades, so initial technical flaws present in earlier buildings may have been eliminated from later ones. Also, the older the building, the longer its exposed parts have had to endure weathering, potentially influencing the physical condition. The building age also gives some indication to trained professionals about the possible presence of hazardous substances in the building.
- **The geometry of the precast concrete elements** may also inform reuse potential. Elements that come in standard and uniform shapes and sizes may be easier to reuse than custom elements with unique features.
- **The physical condition** of the donor building and its structures are a key consideration. If the structures exhibit signs of extensive degradation, deterioration, or reinforcement corrosion, reuse may not be viable.
- **The availability of information** can either encourage or discourage deconstruction and influence the quality of the deconstructed elements. Structural information is needed for both deconstruction planning as well as reuse planning. The availability of original drawings, specifications and calculations in archives can

ease the decision on deconstruction. Conversely, the lack of information can discourage it. If a deconstruction decision is taken nonetheless, chances are that the elements will be damaged in the deconstruction, since the lack of information hampers the planning of effective disconnection methods.

- **Knowledge about the new building**, if one is already in focus, can inform the search and selection of elements to be deconstructed for specific uses and purposes.

A detailed description of the pre-deconstruction audit is given in Vullings et al. (2022), where the focus is on gathering information and processing it into a so-called inventory model of the donor building, which is a 3D Building Information Model (BIM). Key aspects of the pre-deconstruction audit, relevant to the quality management, are summarised next.

Desktop study

The main purpose of the pre-deconstruction audit is to determine what kind of precast concrete elements would be available for deconstruction and reuse in the donor building, i.e. what kind of elements are entering the quality management process and in which quantities. The aim of the desktop study is to gather the design basis, construction records, history, and previous investigations from a variety of sources, such as archival building drawings and documents. This documentation contains information such as:

- Type and number of precast concrete elements;
- Structural connections and joints of the elements;
- Concrete quality (grade);
- Type, diameter, geometry and strength of reinforcement, including cover depth of reinforcement and whether the reinforcement is pre-stressed or not;
- Exposure conditions, and (if available) exposure history;
- Fire resistance of structures;
- Type and thickness of thermal insulation in exterior wall panels;
- Possible presence of hazardous substances;
- Possible repair measures conducted in the past.

Depending on the case, the documentation available in archives and at the building owner may be more or less complete. The type of element will determine which type of information is a priority. For example, reusing load-bearing elements requires information on structural properties and capacity in order for structural engineers to be able to incorporate them in a new structure. Façade elements, then again, may not be load-bearing, so the condition of the elements becomes more relevant. The information required must be considered on a case-to-case basis.

Shortcomings in the archived documentation may be supplemented by various means. Old photographs, on-site visual inspection, and interviewing workers involved in the building's construction (if available) are ways to bridge information gaps. Some material sampling and testing (see Section 2.2) will also always be involved, but the quality of the documentation determines its extent.

Geometry of the elements

The desktop study is the starting point for determining the physical dimensions of the elements (Figure 2 and Figure 3). Gaps in information can be overcome with light detection and ranging (Lidar), i.e. laser, measurements, the use of Total Stations, or even manual measurements (measuring tape). Before taking measurements, the donor building should be stripped from secondary materials, structures and finishes so that the structural frame is exposed. Nevertheless, while the building is still intact, measuring the physical dimensions of elements is only possible on the visible and accessible side of elements, which is a limitation. Drilling small holes across elements may be helpful in that the hole depth can provide the thickness of the element. By properly combining available information, it may be possible to obtain a complete picture.

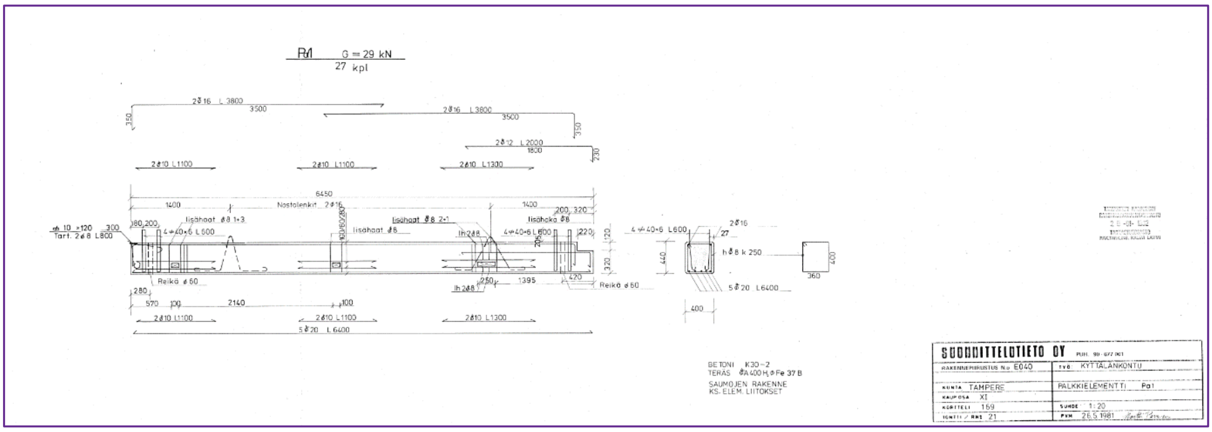

Figure 2. Original detail drawing of precast concrete beam (source: City of Tampere archives).

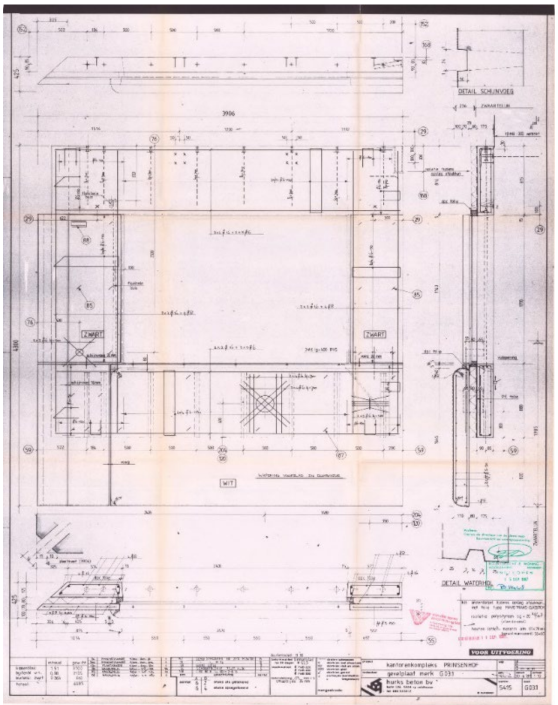

Figure 3. Technical drawing of a facade element (source: Hurks beton b.v.).

Joints and connections between elements

Knowledge about connections between elements is crucial for carrying out deconstruction successfully, as explained in Vullings et al. (2024b). As with the geometry of elements, the desktop study, i.e. observing the original design drawings and calculations, is the starting point. In case of information gaps, some information may be obtainable by measuring the geometry of the elements. It is not, however, possible to obtain a complete picture this way, since connections are largely inaccessible when the structure is in the assembled state. A structural engineer's experience with precast concrete structures, such as knowledge about typically used connections, may be helpful to overcome some gaps in the documentation.

2. 2. Structural investigation and hazardous substances

One of the most essential tasks of the quality management process is to ensure properties of elements, as the properties define what kind of applications the elements can be reused in. Moreover, it is crucial to determine if hazardous substances are present in elements, as they can disqualify elements from reuse if the concentration of substances exceed the limits set by authorities. Even though hazardous substances should, as a rule, be removed before deconstruction, there may be cases where the removal is more warranted after the fact. For example, if the screed or paint on elements contain such substances, it may be removed as a part of the (factory-)refurbishment process. In such cases, the presence of hazardous substances above the limit value influence occupational safety during the deconstruction and refurbishment processes.

In this phase of quality management, structural investigation is employed to evaluate mechanical and durability properties. Its results provide input for structural capacity design and service-life assessment. Second, the presence of asbestos or other hazardous substances is determined to ensure safe working environment and safety of users in new applications. As already mentioned in Section 2.1, the type of structure largely defines which properties must be investigated; this depends, inter alia, on the exposure conditions in the new use and whether the element will be load-bearing or not. If the requirements are low, the extent of the investigation may be reduced, and vice versa. Moreover, the location where deconstruction and reuse take place determines the applicable regulation that must be followed. The relevant EU and national level legal and technical requirements in the ReCreate piloting countries are discussed in Halonen et al. (2023).

Quality of information and extent of investigation

For these reasons, the structural and hazardous substance investigations must be planned on a case-by-case basis. One of the most essential decisions to be made is the extent of investigation and testing (Figure 4), which is related to the reliability of the structural properties, capacity and physical condition of the elements, including the presence of hazardous substances. The decision is underlain and informed by the pre-deconstruction audit (Section 2.1): the higher the quantity and quality of information in the gathered documentation, the more likely the testing requirements may be decreased. If the structural properties, capacity, and physical condition are already known, the investigation can be light and non-destructive (ND), as its purpose is simply to verify that the properties match the documentation. Correspondingly, if the key properties are not known, ND testing may not be sufficient, but semi-destructive (SD) or fully destructive (FD) testing may be required to determine the unknown properties or properties in doubt. In addition, SD or FD testing may be necessary to validate the accuracy of ND testing. Hazardous substance testing, however, always relies on material samples for laboratory tests, and it can be done in parallel with the tests pertaining to structural condition investigation.

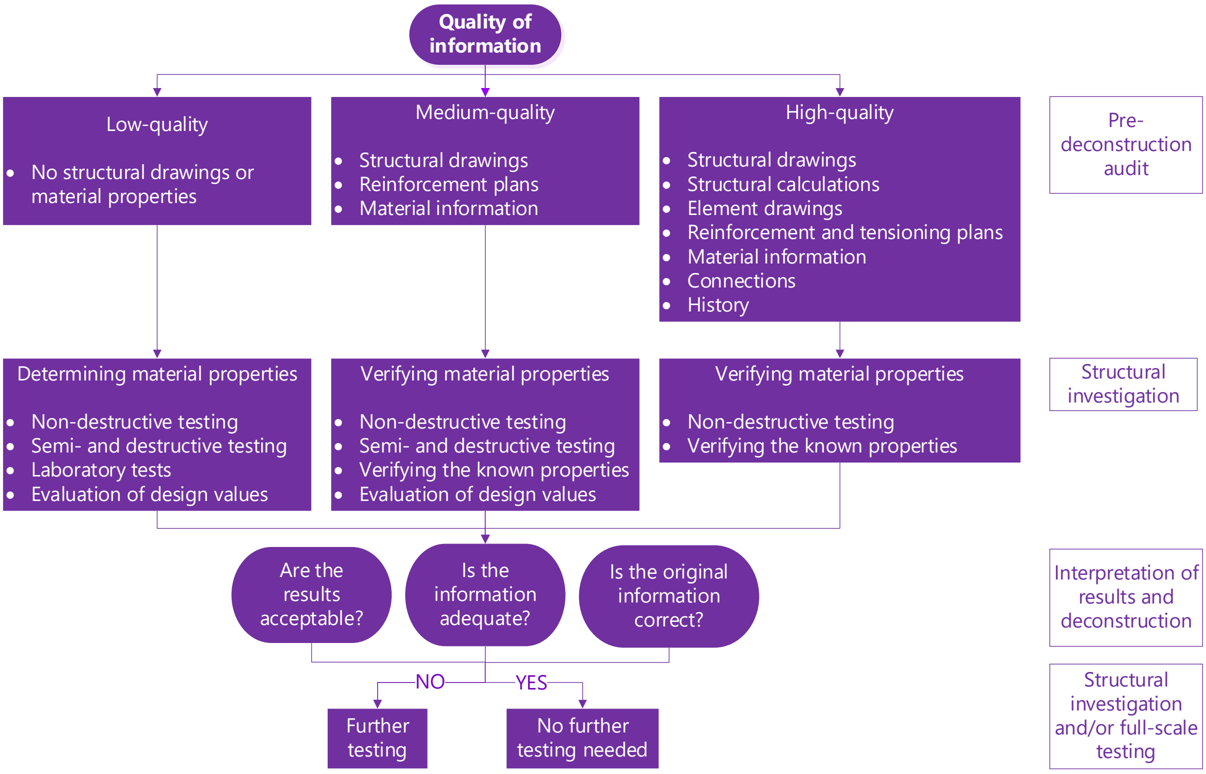

Figure 4. Decision flow chart for testing based on the quality of the information in documentation.

The quality of the information can be divided into high, medium, and low. High-quality means that structural properties, capacity and quality of the elements are known extensively. Medium-quality means that only some of the high-quality information is known. Low-quality stands for nearly complete lack of information. However, sometimes the information available in the documentation can deviate from reality and thus be incorrect. It is possible that either the factory or the site has implemented details in a different way than the structural engineer envisioned while drawing up the plans. Therefore, testing is necessary even with high-quality information. Visual inspection and expertise during pre-deconstruction audit and during deconstruction are vital, as some information can be verified before testing to help define the preliminary extent of testing. Too little testing may risk the quality of the elements and health and safety of workers and users, while too excessive testing may be detrimental to the economic competitiveness of reuse.

Planning and implementation

Careful planning (Figure 5) is essential for successful structural and hazardous substance investigations. The information from the pre-deconstruction audit is vital and should be utilised with a preliminary site visit to set clear investigation objectives. For example, the information from the pre-deconstruction audit can give insights about loads and stresses that may have caused deflections or deterioration of elements, which may need to be included in the testing scheme. Regarding hazardous substances, the age of the building gives indication to trained experts about the typical hazardous substances used in the era. Additionally, the preliminary site visit provides information about the accessibility of testing locations and usability of test methods. A building may still be in use at the time of testing, so the access to certain locations or the use of noise-inflicting methods may be restricted. The planning should consider at least the following questions:

- What is the aim of the investigation (verify known information or determine unknown information)?
- What needs to be measured?
- What kind of materials have been used in the building (are they such that may include hazardous substances)?
- Is there visual or hidden damage?
- What are the test methods?
- What is the sample size?
- Where are the test locations?
- How is the testing conducted (occupational safety and working environment)?

The testing plan is then implemented on one or more site visits. Most of the test methods are standardised in the EU and nationally. The standards and the guidelines, along with the implementation of the testing in the ReCreate's pilots, have been presented in Räsänen et al. (2024). Material samples extracted during the visit(s) are sent to accredited laboratories for testing pertaining to the relevant standards.

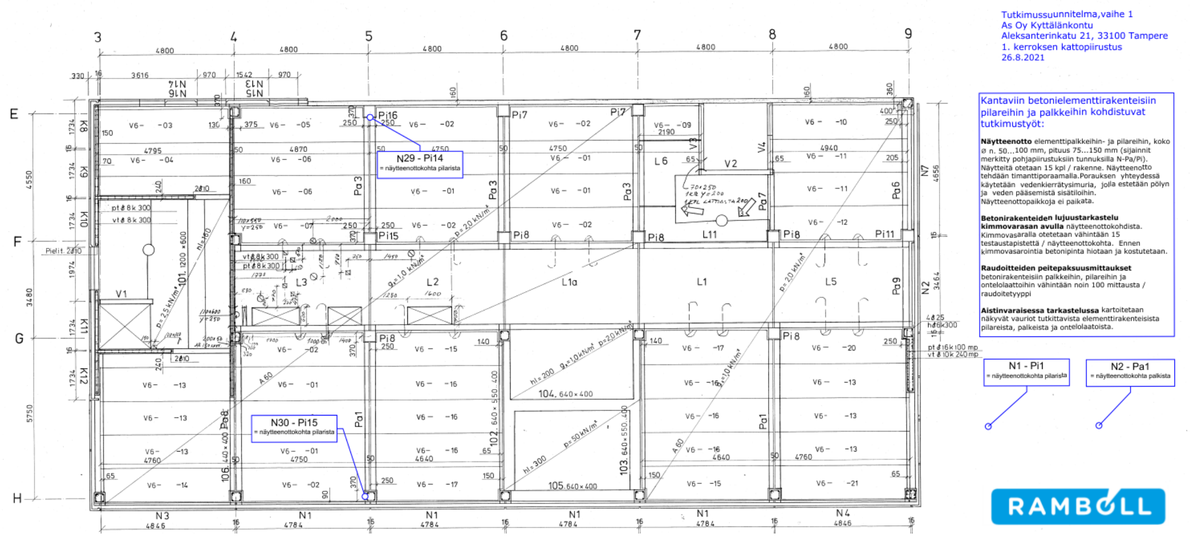

Figure 5. Investigation plan for drilling cores (source: investigation plan, Jani Mikkola Ramboll Finland).

Interpreting the results

After the implementation of the investigation plan, the results must be interpreted. If they do not correspond to the documentation or exhibit high variability, further investigation may be warranted. Therefore, it is essential to involve in the interpretation a qualified structural engineer who can evaluate the results with sufficient knowledge of structural properties, capacity and physical condition of concrete elements. The further investigation can be ND, SD, or FD, including full-scale testing, and the necessary test methods and sampling must be determined on a case-to-case basis.

If no further testing is warranted, the elements can be categorised into three classes based on the test results:

- Class I The element can be reused in the same load and stress conditions as originally;
- Class II The element can be reused in lower load and/or stress conditions than previously;
- Class III The element can be reused if there are no demands for structural capacity, fire safety, service life, etc.

The first class means that no reasonable uncertainty pertains to the results. The structural properties, capacity, service-life and quality of the elements are known reliably. So, the elements can be reused in their original, designed purpose. However, if the results raise some doubts and/or the physical condition of the elements has been reduced, the elements may need to be reused in lower load and/or stress conditions than in the previous application. If the physical condition of an element is very low and there are no expectations for long service-life, and/or the structural properties are low and exhibit substantial variability, the only possibility to reuse the elements may be in applications where there are no demands for structural capacity, fire safety, or service life, etc. Elements must be individually categorized with careful interpretation of the results by an expert.

2. 3. Visual inspection

Visual inspection is an essential part of every stage of the quality management process, including measurements and tests. It is a basic method for detecting possible cracking or other far-advanced defects. Defects should be documented at the time they are noticed, so that their reason and the effect can be evaluated more specifically. Visual inspection should consider at least the following questions:

- Do the elements or connections have cracking or other visible damage?
- What is the location of the cracking or other damage?
- Are the defects local or widespread?
- What can be the reasons for the cracking or other damage?

2. 4. Deconstruction design and execution

Quality management in the deconstruction design and execution phase pertains to three viewpoints. First, it is an essential part of process quality that occupational safety of workers is guaranteed during deconstruction. This aspect is covered in Vullings et al. (2024b). Second, and more at heart of the current report, is ensuring the quality of the elements is preserved during deconstruction and not inadvertently deteriorated. Third, and equally important, is to ensure that the information about the elements, acquired in the previous two phases (pre-deconstruction audit, and structural and hazardous substance investigations), can be associated with the relevant elements also after they have been detached from the building structure and transported elsewhere.

Ensuring information remains traceable

Let us start with the last point, as it needs to be considered before deconstruction begins. Keeping track of the information from the previous phases is easy as long as the building has not been deconstructed (cf. Figure 5). However, there is a need to be able to identify the elements and associate them with the information that pertains to them also after deconstruction, until they reach the new building, i.e. in transport, storage, and (factory-) refurbishment phases. This is essential because elements may look outwardly similar but differ when it comes to technical properties, such as reinforcement. Therefore, the different element types or individual elements must be associated with identification codes that distinguish them and equipped with this code in some physical form, ranging from simple painted markings or conventional (metal or plastic) tags to digital technologies for tracking and tracing (e.g. radio frequency identification, RFID). Developing a labelling scheme as well as the physical tagging is instructed on in Vullings et al. (2024b). It is essential that the physical tags are able to endure the stresses they are exposed to (e.g. weather, some physical wear and tear) throughout the deconstruction, transportation and storage. Some redundancy (e.g. double markings/tags) may be useful to guarantee this. Certain semi-automated workflows and smart tags, such as Quick Response (QR) codes, Bluetooth and Near-Field communication (NFC, a form of RFID), were tested on concrete elements in Sweden (Dervishaj et al., 2023a). Further information can be found in the referenced publication and other outputs from ReCreate's Work Package (WP) 3, which deals with *inter alia* digital information management.

Avoiding inadvertent damage in deconstruction

Even if deconstruction is inherently less destructive than demolition, damage can still be caused by the used machines and lifting equipment (Figure 6 and Figure 7), loads and forces, insufficient support, or weather (Figure 8; see also Vullings et al. 2024b). Such damage may influence the structural capacity or service life of elements, and thus it is essential to avoid. The vast majority of damage can be prevented if support structures, disconnection work methods, machinery, lifting, transport and storage are carefully considered in the deconstruction planning. Apart for the machinery and site-specific factors, the prerequisites for successful deconstruction planning are largely determined already in the previous two phases (pre-deconstruction audit and structural investigation), as the technical information on elements and their connections is gathered. Equally important to careful deconstruction planning is that and work is conducted meticulously as per the plans. If some damage occurs nonetheless, it and its implications for reuse must be investigated separately.

Figure 6. Holes on top of the hollow-core slabs from removing screed in deconstruction stage. Photo © TAU/Aapo Räsänen.

Figure 7. Damage in a wall element cause by deconstruction and lifting. Photos © BTU.

Figure 8. Damage from deconstruction in a hollow-core slab. Photo © TAU/Jukka Lahdensivu.

Lifting, transport and storage

In addition to the deconstruction itself, lifting, transportation and storage are subtasks of the deconstruction phase that can result in inadvertent damage, unless conducted appropriately. They also differ from the conventional demolition process, as structural elements, not waste, are being handled. The challenge in lifting (as a part of deconstruction as well as transportation) is that the lifting anchors in the elements may not exist anymore; they may have been cut off either after the original assembly or during the deconstruction. Therefore, lifting requires consideration and planning. Incorrect lifting and supporting, such as the use of wrong lifting points or support points, can cause significant damage to elements. For example, if beams' lifting points or support points are too close to one another, the ends of the beams may become cantilevered in a way they were not designed to. This may cause too high tensile stresses resulting in cracking, especially if the beam's structural capacity has been (inadvertently) decreased in deconstruction (Figure 9).

Other than lifting, the practices in transportation are comparable to transporting the new elements, so best practice guidelines for new element transportation should be followed.

Figure 9. Support points too close to the midspan (left) and a crack on top of beam caused by this in conjunction with insufficient (inadvertently sawn) reinforcement (right). Photos © TAU/Aapo Räsänen.

After deconstruction, the elements may need to be stored before the new application. During storage, the elements may become exposed to several different stresses that can cause deterioration of condition. These stresses and their nature are well known, as also brand new elements are exposed them in storing before use. However, deconstructed elements may have some minor deterioration from previous use, deconstruction, or transportation, which may make them more susceptible to damage. For instance, water absorption into cracks or hollow-cores can cause severe damage in subzero temperatures when the water freezes and thaws (Figure 10 and Figure 11 – the examples are from the deconstruction phase where plenty of water originates from sawing the joints, but some cracking, though not as extreme, can happen in storage as well). Alternatively, external substances, such as chlorides, may cause deterioration in the long term. In addition to the climate stresses, other stresses, such as stability of the ground in storage, need to be considered. The ground needs to be stable to prevent any inadvertent falling of the elements. The possible stresses present in storage area must be evaluated and if needed, the elements exposure to them must be prevented or limited by e.g. covering the elements. The suitability of the racks and supports must also be ensured. Guidance for this is provided in Vullings et al. (2024b).

Figure 10. Damage in a hollow-core slab from freeze-thaw exposure during deconstruction. Photos © TAU/Emmi Salmio.

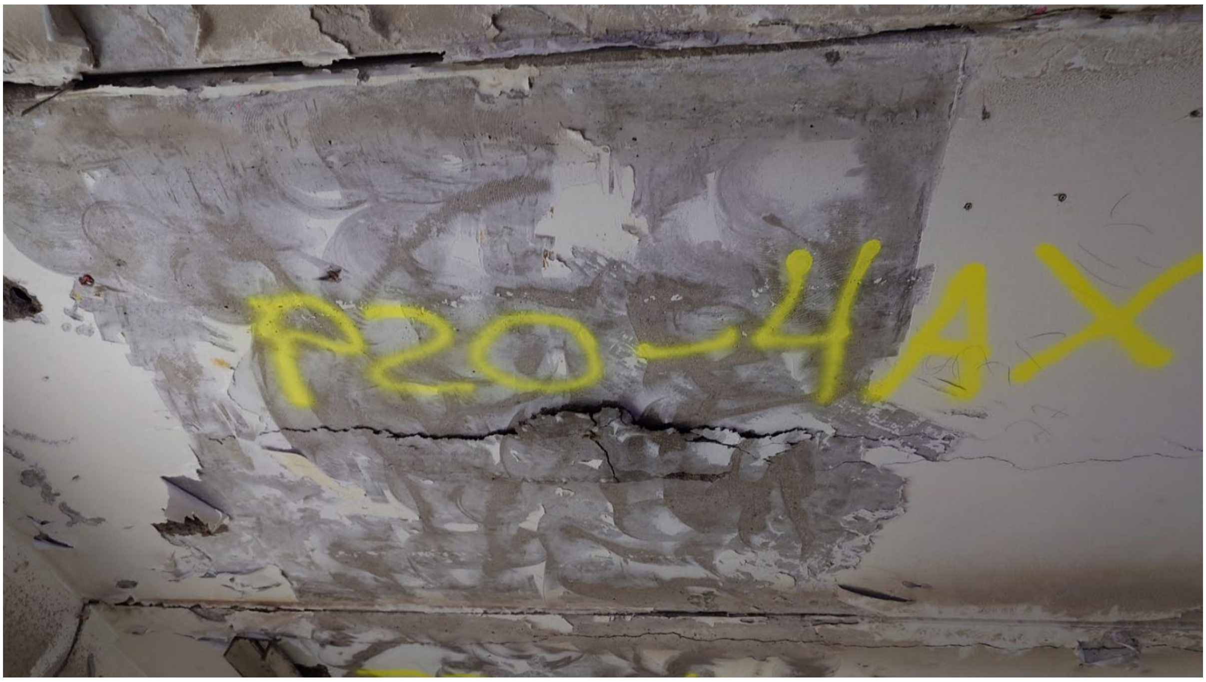

Figure 11. Cracking in a hollow-core slab from freeze-thaw exposure during deconstruction. Photo © TAU/Emmi Salmio.

2. 5. Full-scale tests

If the properties and condition of a donor building's elements cannot be sufficiently evaluated with ND and SD testing on site (cf. Figure 4), FD full-scale testing (Figure 12) may need to become a part of the testing process. Even though it may be rarely needed, it is presented herein as an individual stage of the quality management process because it requires separate planning and documentation depending on the purpose of the testing. Full-scale testing also differs from structural condition investigation in that firstly, the full-scale tests are usually done to the elements in a laboratory, and secondly, the testing specimens (the elements) are destroyed as a part of the process and are thus no longer available for reuse.

The full-scale testing is the only stage in the quality management that may be omitted from the process, as it may not be relevant. The relevance depends on the results of the previous stages of the quality management process. If the behaviour of the elements is in doubt, verification with full-scale tests may be necessary. It may come into play if the structural capacity cannot be evaluated, inadvertent damage has occurred (Figure 13), or new solutions for the reuse, such as connections or the behaviour of elements after repairs and refurbishment need confirmation.

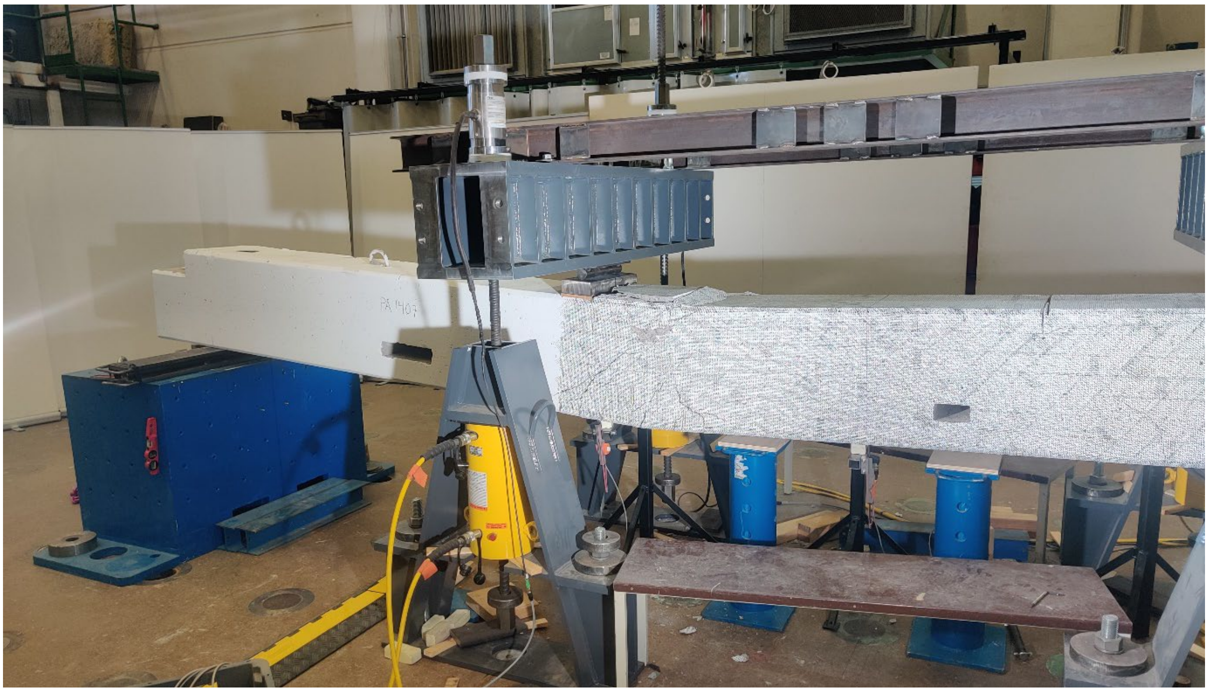

Figure 12. Full-scale testing of a beam. Photo © TAU/Aapo Räsänen.

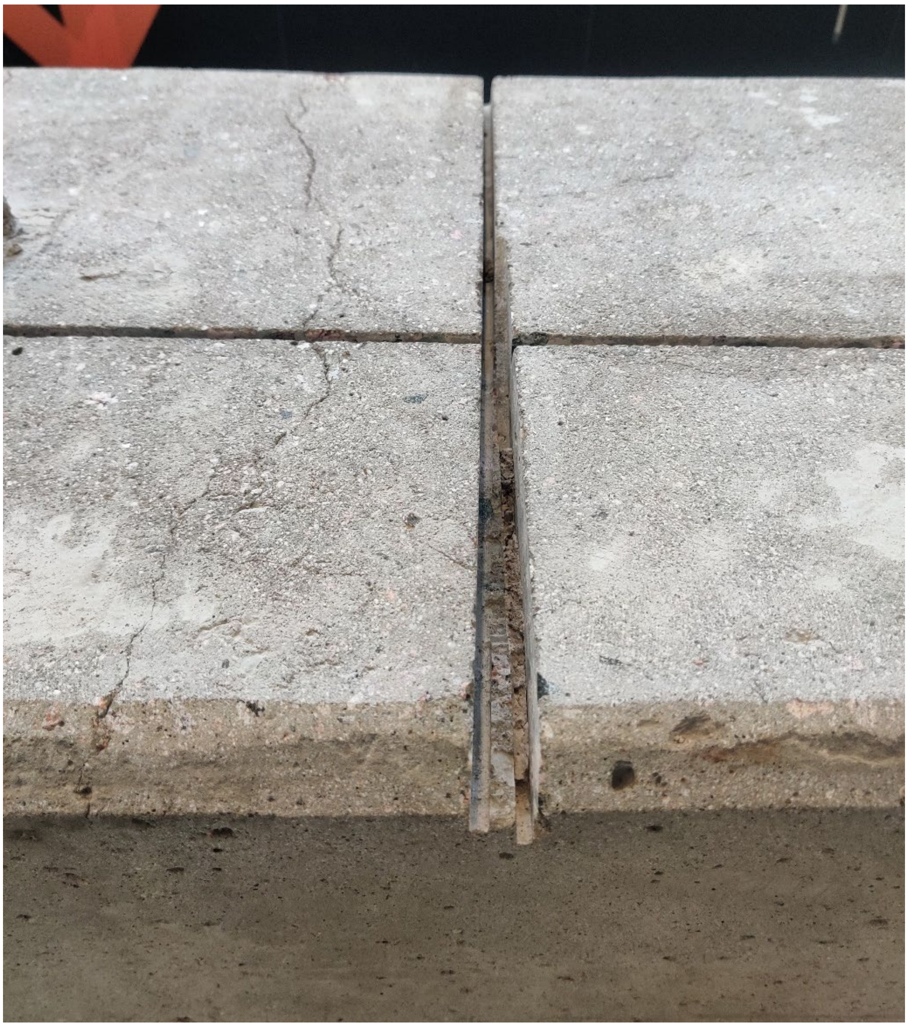

Figure 13. Sawing grooves from deconstruction on top of a beam. Photo © TAU/Aapo Räsänen.

2. 6. Redesign and reassembly

The significance of safety and reliability cannot be over-emphasized when structural precast concrete elements are reused. Reused elements must meet present regulatory requirements for structures. This means that the elements must be 'redesigned', i.e. new design documents must be made for them according to the standards in force. In some cases, the elements may need some refurbishment or strengthening to fulfil the current requirements. If the need is extensive, a decision may be taken to assign the elements to a less demanding use category, where stresses and/or regulatory threshold values are lower.

Gaps between the elements' properties and current regulations typically occur in structures that are intended to separate apartments or fire compartments of a building, since sound and fire insulation requirements have significantly evolved over the years. Existing elements may require additional insulation or increasing the physical resistance of the surface. In addition to the requirements of regulations, deterioration or damage may occur in deconstructed elements, which define the requirements for repair and (factory-)refurbishment. Thus, the structural investigation for condition is a prerequisite for the redesign. However, the decisive requirements result from the intended new use, and the requirements for repair and refurbishment must be evaluated on a case-by-case basis.

The determination of material properties (Section 2.2) is essential for safe and reliable reuse. Design values for redesigning the elements are drawn from the documented information and testing. The original design values can be used if they are available in archived design documentation and verified through testing. If the properties are not known, they must be investigated by testing, and the design values determined from the test results. This work must be undertaken by a qualified structural engineer.

Depending on the type of the element and its connections to adjacent structures, it may not be possible to replicate the original lifting arrangement and/or element assembly. This is because e.g. lifting anchors or surfaces, or connectors may have been damaged or modified in deconstruction. Thus, new connections and lifting arrangements may need to be designed and tested to ensure the behaviour of the new configuration. Connection types and retrofit connectors developed and manufactured for ReCreate's real-life reuse pilots are discussed in another ReCreate deliverable (D5.2).

In addition, high environmental performance, such as low carbon footprint or high level of circularity, are increasingly seen as building projects' essential quality aspect. Reusing building components can make significant contributions to these metrics in new construction projects. Several digital tools are available for buildings' environmental assessment as a part of the design process (see e.g. Dervishaj & Gudmundsson, 2024).

2. 7. Product approval and authorisation

The legal and technical requirements in reusing precast concrete elements, including product approval and authorisation, is discussed in Halonen et al. (2023). At the moment, product approval of reused building components falls under national jurisdiction, although obtaining a Conformité Européenne (CE) mark is also possible for reused products through European Technical Assessment (ETA). Despite differences in national processes, ensuring the quality of the components is always necessary. Careful documentation of each stage in the quality management process is the key to obtaining product approval and authorisation. Comprehensive documentation demonstrates the quality management process and the reusability of the reclaimed elements to authorities. The documentation is also valuable for the future management and maintaining of service-life of the reused elements as a part of a new building. The main documents to evidence the reusability of reclaimed elements to authorities are:

- report on structural condition investigation and material properties,
- report on hazardous substances investigation,

- refurbishment design and inspection documents of elements,
- report on full-scale tests (if any have been needed),
- redesign documents: structural calculations and technical drawings of reused elements as a part of a new building's design.

2. 8. Documentation

The importance of documentation was already discussed above in Section 2. 7. as a part of the authorities' approval. However, the documentation is essential not only for this purpose, but also for quality management at large. Different persons may be responsible for different stages of the quality management process, and the information from previous stages may be necessary for the process to be able to proceed efficiently. Therefore, it is essential to ensure information transmission between stages and that no information is inadvertently lost.

In this context, the utilisation of digital technologies, such as BIM, can facilitate information storing and sharing between participants in a reuse project. The BIM model can be used to store a variety of information, such as tracking and tracing information for building elements, material properties of ND, SD and FD tests, as well as links to drawings and documentation that are stored in a shared repository in the cloud (a Common Data Environment, CDE). The information needs when using BIM for the reuse of precast concrete are investigated through the Level of Information Need standard and framework EN 17412-1:2020 in the ReCreate paper Dervishaj et al. (2023b).

3. Discussion

The quality management process outlined in this document has been developed and tested thoroughly in ReCreate's Finnish pilot. However, many similar measures have been taken in all ReCreate piloting countries, but not necessarily in the presented order. The following discussion on the quality management process is based on piloting actions described in Vullings et al. (2024a) and Räsänen et al. (2024) and those undertaken in ReCreate's WP5 for redesign and reassembly, the deliverables of which are not yet available at the time of writing this report.

Pre-deconstruction audit

Pre-deconstruction audits were conducted in all piloting countries. Technical drawings and other design documentation, such as technical calculations, were studied widely before taking other action. This was found to benefit the next steps, even though the availability of technical documentation varied. In the Dutch pilot, all documents of donor building were available. In Finland and Germany, some documents of the donor building were missing. In Sweden, documentation was available for the prefabricated concrete construction system used for the donor buildings. Drawings were available for similar buildings, but not specifically for the donor building. This should lead to different extents of testing to ensure material properties of elements, though this principle was not fully achieved in ReCreate's pilots (in particular in the Swedish pilot). High-quality information on reclaimed structures may need only ND tests and some samples for laboratory test to ensure material properties reliable. Low-quality information or no information at all should lead to more comprehensive testing on site and laboratory to determine unknown properties.

Recommendations for best practices in the pre-deconstruction audit have been given in Vullings et al. (2022).

Structural condition investigation and hazardous substances

Compressive strength of concrete is needed in the elements' redesign, and therefore, it is to be considered as essential to measure. Compressive strength of concrete was investigated in all ReCreate pilots by drilling core samples from elements, which were tested in a laboratory. The number of samples varied substantially between countries. In Finland and Germany, also ND tests were performed to the same end with a rebound hammer. ND testing should always be considered as the first option in all testing to minimise the damage and cost of the investigation. Nevertheless, also SD (laboratory tests of samples) and FD methods may be needed to verify the results of ND testing and to reliably determine unknown properties. The best practice, considering the variation in the number of samples and tests, will be the topic of in another ReCreate Deliverable (D4.3).

Durability properties were investigated in all ReCreate pilots as well. Cover depth of reinforcement and carbonation depth of concrete were studied comprehensively in all pilots. In Sweden, also chloride content of concrete and in Finland, freeze-thaw resistance of concrete were studied. Cover depth of reinforcement influences the fire resistance and structural capacity of concrete elements. As of writing this report, the fire resistance of the reclaimed elements has not been tested. The fire resistance evaluation will be carried out with computational methods in the cases where it will be necessary.

Hazardous substance survey and removal is a standard procedure in every building demolition. However, these processes have been designed to serve the end purpose of demolition, i.e. to ensure demolition workers' and nearby residents' non-exposure, and to guarantee the concrete rubble can be reutilised as material (e.g. in roadbeds or mixed into new concrete along with virgin aggregate). The threshold values for hazardous substances in these applications may differ from reuse, which is why hazardous substance survey and removal should also be developed from reuse point of view. For example, in ReCreate's Finnish pilot, the screed on hollow-core slabs was removed because the presence of volatile organic compounds (VOCs) was detected. This would not have been necessary in a normal demolition project, and thus possible hazardous substance need to be considered based on housing health and using guidelines related to building renovation. In ReCreate's pilots, hazardous substances have been studied according to existing national demands and guidelines. The list of studied and detected substances varies between countries. Due to the lack of EU guidelines or standards, this topic will be addressed in more detail in the future ReCreate Deliverable 4.3.

Visual inspection

Visual inspection of the elements in the donor buildings was performed in multiple stages in all ReCreate pilots. The first inspection was carried out when the donor buildings were engaged in deconstruction. After the non-structural materials had been stripped, the visual inspection was repeated. In addition, the elements were inspected before and after deconstruction and were thus fully visible. Further visual investigation was also performed after the elements were transported. The core samples drilled from the elements were also inspected visually before testing, as were the elements themselves before full-scale testing. However, the documentation of visible defects was not done to a sufficient degree, and it was noticed to be important in each stage. For instance, in the Finnish pilot, diamond sawing induced grooves on the top of beams, affecting bearing capacity negatively, which could have been avoided through more frequent and thorough visual inspection.

Guidelines pertaining to cracking of hollow-core slabs were developed in ReCreate's Finnish and Dutch pilots. Prestressed Concrete Institute (PCI) (1983) has published figures on types and locations of cracks in hollow-core slabs (Figure 14), which were capitalised on in the case of reclaimed slabs, too. Checklists for the visual inspection of reclaimed hollow-core slabs have also been presented in Sweden by Suchorzewski et al. (2023) (Table 1) and in the Norwegian standard NS 3682:2022 (Table 2). In ReCreate's Finnish pilot, guidelines for cracks of beams were also developed.

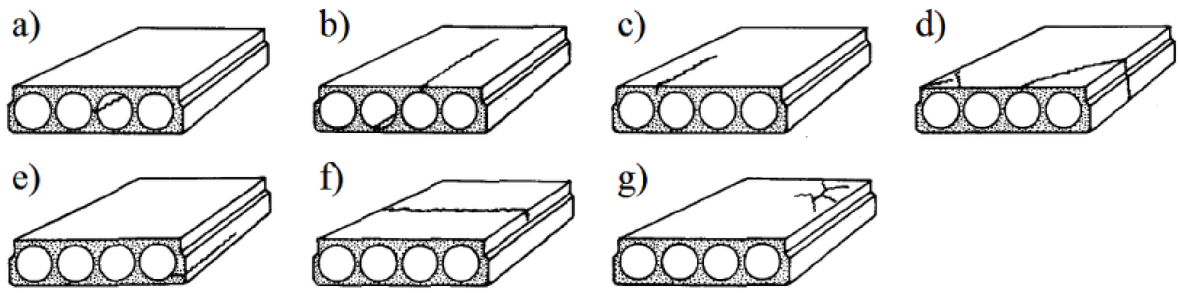

Figure 14. Cracking types and locations in hollow-core slabs (PCI, 1983).

Table 1. Classification system for reclaimed concrete elements proposed in Sweden (Suchorzewski et al. 2023).[1]

Class	Service-life	Extent of cracking	Target environment
DCE Gold"As new"	The degradation of concrete cover will take more than 100 years according to theoretical model calibrated on the data from the structure.	Cracks lower than 0.05 mm do not affect the transport properties of concrete.	The same or milder environment that in the donator structure (ex. parking deck placed as a slab in residential building).
DCE Silver"second-hand"	The degradation of cover will take less than 25 years. The detailed structural analysis is required to correctly determine the bearing capacity. Requires detailed analysis of service-life with special attention to humidity conditions.	Cracks larger than 0.05 mm which may affect the transport properties of concrete. Increase of diffusion coefficient required based on literature.	The element can be subjected to more severe environment in the storage time between dismantling and installation that should be included in the corrosion risk calculation.
DCE Bronze	The cover is degraded or will soon be degraded. The assessment focuses on corrosion risk and consequences (reinforcement cross-section reduction). The static calculations should include reduction in reinforcement. Refurbishment recommended before reuse.	Cracks wider than 0.30 mm reducing functionality of the concrete cover in corrosion protection. Recommended cracks repair.	Element to be placed in aggressive environment (ex. residential slab to be exposed to salt or frost).

Table 2. Example of a checklist (A 3: Dismantling of hollow-core slabs – after completion work) (NS 3682:2022).

Responsible (person and company):			
E-mail:			
Phone number:			
Date:			
Signature:			
Control aspect	**Taken into account**		**Measure**
	Yes	**No**	
Have elements which have been identified as waste been sorted out?			
Have elements which have water damage, visible cracks or damage in the zone which shall be used been sorted out?			
Have all elements been numbered in accordance with drawings which show their location in the original building?			
Specify energy consumption (electricity, quantity and type of fuel, etc.), linked to the work to dismantle elements.			

[1] In addition to the cracking of concrete, the Swedish classification also considers the service life of hollow-core slabs in the targeted environment. The service life prediction is based on the cover depth of prestressed steel and the carbonation rate of concrete or the chloride penetration rate in concrete. However, the corrosion of prestressed steel is the only factor in the classification that can disqualify an element from reuse in the targeted environment.

Out of the ReCreate countries, Germany is the most experienced in the reuse of concrete elements and thus has a long track record on guidelines development for visual inspection. A classification into four categories, which is useful for visual inspection in each stage, is presented in '*Bauzustandsstufenkatalog'* (catalogue of structural condition) developed by Mettke et al. (2008):

BZS 1: Functionality according to the projected parameters provided:

- No defects or damage,
- Slight reduction in the quality on the surface,
- Visible hairline and drying cracks.[2]

BZS 2: Functional capability provided:

- Damage, localised spalling on the surface,
- Outer visible surfaces partially weathered,
- Slightly marked, localised rust lines,
- Visible steel fasteners slightly rusted on the surface,
- Minor localised moisture penetration.

BZS 3: Limited functionality:

- Extensive damage to the surface,
- Wide, partly continuous longitudinal and transverse cracks, but locally limited,
- Outer visible surfaces heavily weathered with flaking,
- Visible steel fasteners loosened and rusted.

BZS 4: Functionality no longer guaranteed:

- Extensive damage with extensive destruction of the structural element,
- Deep, continuous longitudinal and transverse cracks across the entire cross-section,
- Reinforcement often exposed, heavily rusted with reduced cross-section,
- Extensive moisture penetration and oil residue.

Some defects, like broken edges in hollow-core slabs and wall elements, were found in all pilots after deconstruction. These defects were caused by the deconstruction works. Therefore, it is important to have a systematic visual inspection process for the deconstruction site. The inspection should be carried out by qualified structural engineer, and documentation be thorough with measurements and photos. In most cases, elements with small defects are still reusable.

[2] Such cracks are normal in all concrete structures, also new ones.

Deconstruction design and implementation

Visual inspection of the detached elements was the main quality control method during and after deconstruction in all ReCreate pilots. Deconstruction techniques varied between countries mostly because of national traditions and differences of joints and connections. In the Finnish pilot, the arrival of winter (subzero temperatures) and freezing of water from diamond sawing induced extra difficulty. Afterwards, it could be concluded that in the Nordics and other similar climates, deconstruction should be carried during spring and autumn, when the cold weather does not cause challenges. In addition, diamond sawing of seams between hollow-core slabs caused some grooves on the top of beams in the Finnish pilot, inadvertently cutting top reinforcement bars of the beams. The inadvertent damage was not detected, reported, or documented at the deconstruction site. With better instructions and site supervision, such grooves could have been avoided in the first place.

Lifting of beams and other elements was mostly not possible using original lifting anchors because they had been cut off after the first assembly. Commonly used lifting accessories for hollow-core slabs, which grab a slab by its grooved side profile, could also not be used because of the presence of grout in the profile in the Finnish and Dutch pilots. In the Dutch pilot, the presence of a structural topping was another reason why standard lifting accessories could not be used. ReCreate-developed lifting accessories were therefore used together with lifting chain and slings. They enabled lifting the elements safely but also resulted in numerous holes to be drilled in the elements, which must be repaired before or as a part of the reuse in a new building.

Based on the experience from the pilots, it is highly recommendable to have a qualified structural engineer as a quality controller on the deconstruction site. The task of the engineer is to inspect the deconstructed elements visually and to document any defects before sending the elements forward.

Full-scale tests

Full-scale tests were implemented in the Finnish and Dutch pilots, but not in the Swedish or German ones. In the Dutch pilot, bending load tests were performed on hollow-core slabs. In Finland, bending load tests have been carried out on hollow-core slabs and beams, where full-scale have also been planned for columns, though they are awaiting execution at the time of writing.

As already mentioned, grooves from diamond sawing were inadvertently induced on top of beams in the Finnish pilot, reducing the cross section of the beams. Full-scale tests were also carried out to uncover the structural behaviour of the beams without repair as well as in a repaired state (the grooves patched with grout).

No tests have been or will be made related to sound insulation, fire resistance or building physical performance of elements. Many of these aspects can be studied with the help of computational methods if necessary due to the requirements of the new use.

The required safety and thus, the need of full-scale testing depends on the demands of new construction that reclaimed elements are assigned to. More information gathered from testing will result in higher safety. Local authorities may have a stance on the test needs, too. The Norwegian standard NS 3682:2022 for reclaimed hollow-core slabs defines, as the minimum, the full-scale testing of 2% of slabs but always at least three slabs. However, if the reclaimed elements are undamaged and their bearing capacity and/or other relevant technical properties can be uncovered through ND and SD tests (material sampling), full-scale testing may not be necessary.

Full-scale testing may also be necessary to ensure the behaviour of newly developed connections, if any are used. However, if standardised connections are used, further testing may not be warranted.

Redesign and reassembly

At the time of writing, ReCreate pilots are mainly between the deconstruction and reuse phases. Therefore, this and the next subsection are yet unable to discuss actual implementation in the pilots in a comprehensive manner. However, already known viewpoints can be discussed now, and the actual implementation will be reported in the deliverables of ReCreate's WP5.

Reclaimed elements must be structurally redesigned, i.e. new structural calculations done, using the present Eurocodes. Usually, some differences exist between the principles of the Eurocodes and the original design conducted according to national codes in force at the time of manufacture. Therefore, it is necessary to ensure a sufficient safety factor for structures. Redesign can be carried out using originally designed material properties, which have been verified with testing. Alternatively, material properties determined through different tests, including full-scale testing, can be used. In pre-stressed concrete structures, such as hollow-core slabs, residual pre-stress in an element is also important as a structural property because the bearing capacity depends on it. The loss of prestress needs to evaluated if there is a doubt that it could be significant. The test methods for evaluating the loss of pre-stress will be studied at TAU and TU/e.

During deconstruction it was noticed that original lifting anchors were often damaged or had been cut off after the first assembly. Moreover, hollow-core slabs could not be lifted with the same lifting system that was used in the first assembly. Several safe lifting methods and new lifting systems were designed to ensure safe lifting and reassembly of elements, see Vullings et al. (2024a) for details. In the Finnish pilot, newly developed lifting system for hollow-core slabs was approved by authorities.

ReCreate pilots' reclaimed elements will need some refurbishment before reassembly. The most common refurbishment needs are holes in elements as well as broken corners. Refurbishments must be designed by qualified structural engineer, and all repairs carefully conducted and documented. In cases where the refurbishment is intended to influence (improve) the bearing capacity of the structure, such as the beams in the Finnish pilot, full-scale tests are also recommended, unless the principle of behaviour after refurbishment is already known from previous research.

All aspects pertaining to the redesign of structures and the design of new connections will be discussed thoroughly in the deliverables of ReCreate's WP5.

Product approval and authorisation

The processes of securing the product approval are currently national. The introduction of a more systematic, European process would be beneficial for upscaling reuse in the EU and beyond.

So far, the discourse on the approval and authorisation has been most extensive in Finland. Several discussions with authorities have been conducted in conjunction with ReCreate's WP8 (pertaining to regulation) as a part of a larger Finnish debate as to how the EU Construction Products Regulation (CPR) applies on reused building products. Based on the discussions, site-specific certification of reused elements was confirmed as the method of authorities' approval by the Finnish Ministry of the Environment, which put out a media release to inform companies and local authorities (Ministry of the Environment, 2022; see also Halonen et al., 2023). More recently, discussion about the implementation of the site-specific certification was initiated with local building inspectors. The documentation of the quality management process, as suggested in this report, was agreed to be the key. In a similar fashion, extensive dialogue was conducted in the Finnish pilot with national, regional, and local environmental authorities about the potential waste status and the need and nature of 'End of Waste' (EoW) criteria for deconstructed elements. This resulted in the authorities' conclusion that if the quality management process is systematic (such as the one suggested in this report), the elements will not lose their status as construction products. However, elements deconstructed without a comprehensive and reliable quality management process in place may still be classified as waste. Further details on this will be provided in another ReCreate deliverable (D8.3).

Since building projects with reuse of precast concrete elements have been implemented in Germany over three decades (see e.g. Mettke et al., 2008), tacit processes are in place in regions where such projects have been implemented for handling the approval and authorisation (see Halonen et al., 2023). In the context of ReCreate, the discussions in Germany have been related to the need of CE marking or other necessary testing carried out by a Technical Control Organisation or quality control of companies.

In the Netherlands, reuse of building components is in practice allowed even if the regulatory situation and status is not crystal clear (for details, see Halonen et al., 2023). The approval of authorities has not yet been discussed in the context of ReCreate's Dutch reuse pilot, but this will take place in due course.

Since ReCreate's reuse pilot in Sweden was a temporary structure, the regulatory demands posed on it do not compare to those of permanent structures. However, a discussion on the Swedish regulatory situation can be found in Halonen et al. (2023).

The experience on approval and authorisation acquired through ReCreate's reuse pilots will be reported in full on another ReCreate deliverable (D8.3).

4. Conclusions

This report has presented an outline for the quality management process of reclaimed precast concrete elements. The process is tested thoroughly in ReCreate's Finnish pilot and in parts in the other pilots in Sweden, the Netherlands, and Germany.

The pre-deconstruction audit is the first step in the process. The quality of documentation gathered as a part of the audit will guide the definition of necessary tests for either verifying and/or determining the material properties of elements. High-quality information will likely lead to smaller test needs, the use of ND testing methods, and only some SD material sampling for laboratory tests. Medium-quality information or no information at all calls for more extensive ND tests and larger SD testing and sampling to achieve reliable results on material properties.

Visual inspection should be carried out in all the stages of the quality management process. Guidelines are available for classifying cracks and other defects of elements. Based on the experiences of ReCreate's pilots, it is highly recommended that a qualified structural engineer does the inspection and documentation, in particular on the deconstruction site. It is vital that information is available to all parties during the whole process.

Material properties and actual physical condition of structural elements must be studied with suitable methods and extensively enough to obtain reliable values for structural redesign (structural re-calculations with current Eurocodes). ND testing should be considered as the first option in all testing to minimise cost as well as damage to elements. SD (laboratory test of material samples) and FD methods should be used to verify the results of ND testing and to obtain information if the properties are not available in archival documents. The variation in number of samples and tests will be determined in this report's 'sister' deliverable, D4.3.

Hazardous substance surveys are a standard practice in all ReCreate piloting countries, but national demands and guidelines vary country by country. Furthermore, hazardous substance surveys should be developed to better cater for the specific needs and purpose of reuse. This topic must, too, will be discussed in more detail in the other report, deliverable D4.3.

During deconstruction, serious attention should be given to guiding workers to meticulously follow the correct work processes in order to guarantee their own safety as well as to avoid inflicting inadvertent damage. Many kinds of defects can be avoided with proper guidance and supervision.

Full-scale testing can become a part of the testing process if the quality of elements cannot be evaluated with ND and SD testing (sampling). Full-scale testing must always be done in a laboratory and is laborious and costly. This is the only stage in the quality management process that can be omitted based on the results of the ND and SD tests, as it may not be necessary for ensuring the structural behaviour.

Based on the results of the previous phases, design values can be obtained for structural redesign, and redesign can be carried out according to Eurocodes. Careful documentation of the methods, processes and results of the previous phases of the quality management forms the documentary basis for the approval by authorities.

While the current report has laid the foundations by providing an outline of the quality management process, a best practice proposal of quality management, including recommended methods and sample sizes, will be the topic of the 'sister' report, ReCreate deliverable D4.3.

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