Reuse of decommissioned offshore steel components for new buildings: A case study

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Abstract. Reuse process of structural steel members, which are extracted from decommissioned offshore platform, for new apartment building is presented in this paper. An index is introduced to assess the technical feasibility of the reuse process of offshore steel components to steel buildings. The applicability and significance of the reuse process is demonstrated by a real case study. Steel columns of a new four-storey apartment building are replaced by selected members from recently decommissioned offshore platform in this case study and hence feasibility, cost benefits and environmental advantages are investigated. Utilization ratios of selected pre-used columns shows that those columns have more than sufficient capacities to withstand the loads. This indicates that considered decommissioned module of offshore topside is applicable for similar size of new buildings. The results indicate significant environmental benefits such as reduction of the CO_2 emission, low global worming potentiality, and etc. The reusability index of the considered case study is 51.5%, which shows marginal feasibility of reuse, and this can be increased, if the reuse process is industrialized and streamlined by the offshore decommisioning companies. Three ways are proposed to industrialize and streamline the reuse process in the latter part of this paper.

1. Introduction

Construction industry is taking countless measures to reduce the carbon footprint as world is currently facing environmental and climate challenges. Literature has reported that one third of the CO_2 emissions are produced by the construction industry [1-3]. Production of structural steel requires quite lot of energy which emit approximately three billion tons of CO_2 each year [4]. This amount is approximately 8% of all CO_2 which is being released by human beings in the world. Researchers gave a high attention for hydrogen breakthrough ironmaking technology to decarbonize the common steel production process [4] and this technology is not yet fully established as it may increase the production cost. Therefore, construction industry should pay attention about other alternatives to reduce the CO_2 emission. Reuse of steel members of decommissioned structures is another way to reduce CO_2 emission. Use of structure or part of it after its first use (i.e pre-used) is defined as “Reuse” in this paper and this differ from the “Recycling” process. Life cycle of steel commonly has five main phases such as raw materials, steel production, manufacturing, service life and recycling. The phase 1, 2 and 4 are energy demanding and release lot CO_2. Therefore, these phases can be bypassed by reusing the pre-used steel for new steel buildings.

There are methods and European recommendations have recently been developed to reuse steel, which were taken from decommissioned steel building, for single-storey onshore buildings [4-6]. However, there is a doubt that sufficient amount of pre-used steel can be obtained from only decommissioned onshore structures. Another source of pre-used steel supply is decommissioned offshore oil and gas platforms. Majority of offshore platforms are reaching to end of design life and decommisioning is now required (i.e currently 12% of offshore installations, which is 88 oil platforms) [7,8]. Around 2000 offshore oil and gas platforms in the world are planned to be decommissioned by year 2040 [9] and this could be a big source of supply for reuse process/industry.

Repurposing of steel members is an important process when reusing offshore steel in component level. This process requires different attention on the feasibility assessment (i.e reusability assessment) which includes comprehensive degradation assessment, remaining capacity/strength analysis and re-design procedures. Reusing offshore steel for new onshore buildings may provide economic benefits, in addition to above discussed environmental benefits. However, there are lack of studies to check the feasibility and quantify both environmental and economic benefits, when reusing offshore decommissioned steel members/structures for new onshore buildings.

Therefore, main objective of this paper is to investigate technical feasibility, advantages, and disadvantages, when using the reclaimed steel members from decommissioned offshore platforms to new onshore buildings. A real-life case study is performed to quantitatively assess the feasibility/technical reusability and environmental benefits. This case study only focusses analysis and design of new apartment building with reclaimed steel, not on designing the building for the purpose of being reused. The paper first discusses the reuse methodology. The details and the results of the case study is presented. Comparison of the results and discussions are shown in the latter part of the paper.

2. Reuse Methodology

Generally accepted reuse practice is required to streamline and industrialize the supply of reuse offshore steel in the building industry. This practice should include all the stages/operations from pre-decommissioning assessment of the donor platform to delivery on new building construction site, based on a reusability assessment. The reusability assessment consists of three major aspects, such as feasibility (i.e. technical aspects), cost benefits and environmental impacts. The major operations of the reuse process are decommisioning, demounting, handling & manipulation, separation & cleaning, redesigning & repurposing, modification, quality check, and geometric verifications. The flowchart of the reuse process is shown in Figure 1. The more details of each operation and related conceptual framework are presented in recent publication of the authors [8,10].

2.1. Reusability index

The technical feasibility of the reuse process can be assessed by a recently proposed approach, which is based on reusability index [5,8]. This index involves assessing and quantifying above mentioned individual operations (i.e reusability performance categories) of reuse process based on own feasibility. The reusability index r is defined for a single member as,

$$r = \sum \rho_i w_i \tag{1}$$

where ρ_i is the feasibility of each performance categories, which is graded from zero (impossible) to unity (very easy), w_i is the weighting factors of the individual performance categories. Generally, quantitative assessment of contributing parties, which are involving in each operation of the process, should be required for determining relevant values for ρ_i and w_i. The grades of ρ_i are divided by 20% increments and differences between each grade are clearly tabulated in the original article published by Technical Research Center of Finland [5]. The proposed values for weighting factors, w_i of each operation of the reuse process are presented in the Section 2.2.

The reusability index for entire structure (R) is defined as [5,8],

$$R = \frac{\sum m_i r_i}{\sum m_i} \tag{2}$$

where m_i is the weight of the structural member and r_i is the reusability index of i^{th} structural component calculated as defined in equation (1). The final reusability index is case-dependent.

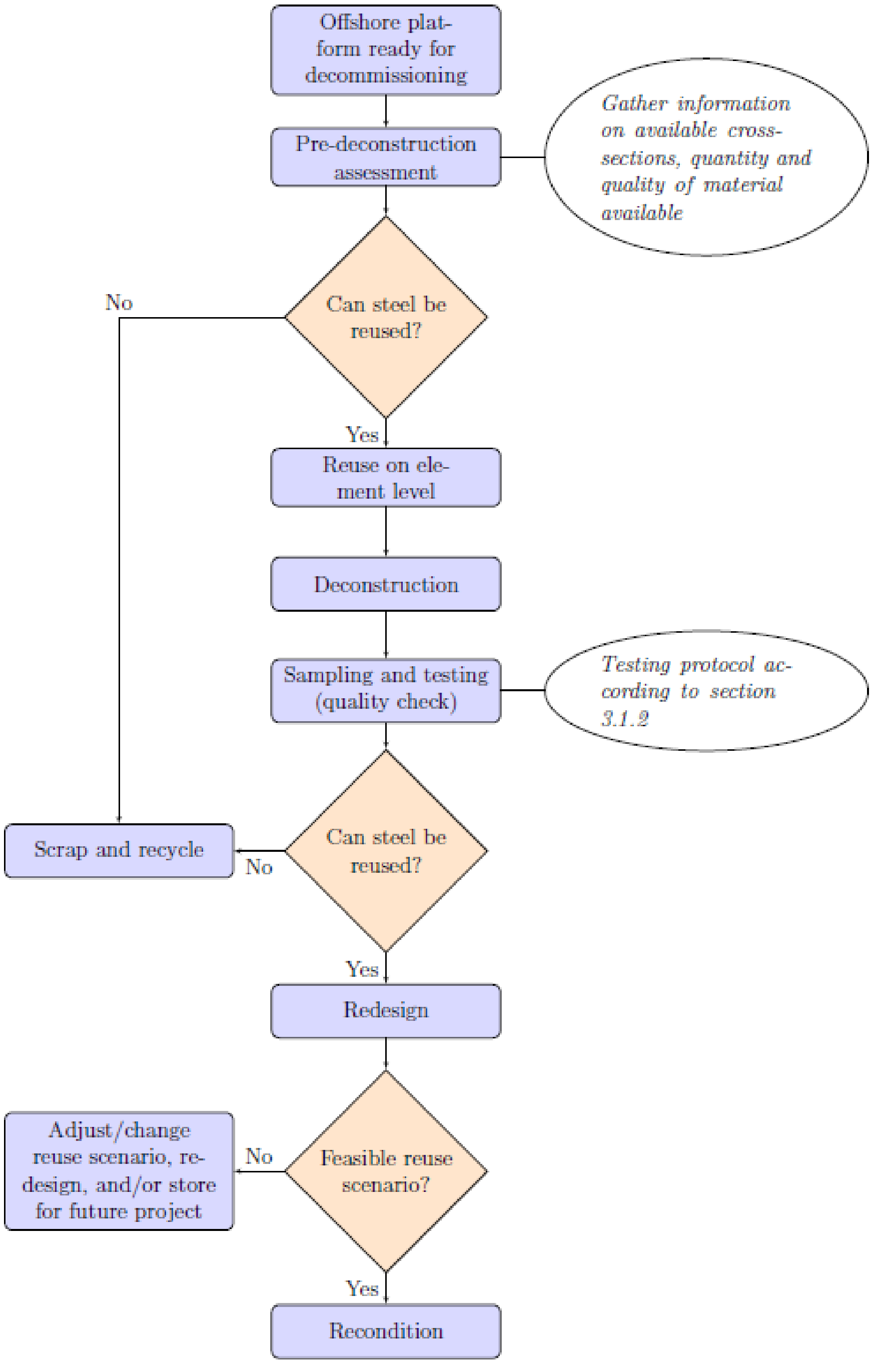

Figure 1. Reuse process for steel members from offshore platforms

2.2. Proposed weighting factors

The weighting factor w_i ranks the significance of each operation (i.e performance category) of reuse process and sum of w_i of each operation is equal to unity. Offshore steel structures are generally subjected to harsh marine environment. Therefore, quality check operation/performance category has a higher potential weightage than other operations specially when consider the reuse process of offshore steel. The modification and repurposing performance categories should be weighted lower than other categories in the process as reusing element/member level (i.e. beams and columns) requires less effort and planning than structure or module levels. The proposed weighting factors for reusability assessment offshore steel are shown in Table 1.

Table 1. Proposed weighting factors

Performance category	Weighting factor (w_i) %
Deconstruction	25
Handling and manipulation	10
Separation and cleaning	10
Redesigning	10
Repurposing	5
Modification	5
Quality check	30
Geometry check	5

3. Case study: Reuse of offshore steel for new apartment building

3.1 Considered apartment building

An apartment building, which is part of Nybyen housing project, is chosen by Sweco AS for this case study. It is a four-storey building which consists of 11 separate apartments. The overall length, width and height of the building are 23m, 12m and 12m. The building is designed by concrete floors supported by steel columns as shown in Figure 2. This type of building is very common in Norway. Therefore, results (i.e. feasibility assessment, environmental benefits and cost aspects) of this case study can be applicable for many other apartment buildings in Norway and this is one of the major reasons to select this building for this case study. The objective of this case study is to check the feasibility of replacing all the steel columns of original design by decommissioned offshore steel columns and hence compare/discuss the environmental and economic benefits, pros and cons. The floor height is around 2.7 m and 69 steel columns with steel grade S355 are used in the original design. The total weight of the new columns is 5220kg. The different types of cross sections used for the columns are shown in master's thesis of the first author [10].

Figure 2. 3D model of considered apartment building

3.2 Structural analysis of original building/design results

The dead, imposed, wind and snow loads were calculated, and ultimate limit state analysis of the building is performed by finite element method employed structural analysis package, FEM design [11]. The steel columns are subjected to interaction of axial force and biaxial bending. Therefore, individual buckling (stability) checks were performed using the equations 6.61 and 6.62 which is given in clause 6.3.3 in the Eurocode 3 [12]. Hence, corresponding utilization ratios (UR) of the steel columns are obtained for the all the columns in each floor. The obtained UR for most critical columns (i.e. which has a UR more than 0.7) are assigned an ID and shown in Table 2.

Table 2. Internal forces and utilization ratios of critical columns of original design

Column ID	Floor	Column type	N_{Ed} (kN)	$M_{y,Ed}$ (kNm)	$M_{z,Ed}$ (kNm)	UR (%)
1	2	RHS200x100x10	594.4	12.81	3.56	85.3
2	2	RHS200x100x10	850.1	18.21	0.56	98.3
3	2	RHS200x100x10	729.0	0.79	5.49	81.3
4	2	RHS200x100x10	697.3	0.90	4.87	76.7
5	2	RHS200x100x10	438.4	1.64	7.79	67.5
6	2	RHS200x100x10	595.9	1.48	13.83	73.8
7	3	RHS150x100x10	429.3	17.84	17.46	93.1
8	3	RHS150x100x10	607.5	11.33	14.95	97.9
9	3	RHS150x100x10	504.8	2.43	5.93	73.8
10	3	RHS150x100x10	474.4	1.19	4.79	68.2
11	3	RHS150x100x10	443.1	1.22	12.86	71.7
12	4	SHS100x100x10	273.8	8.14	11.85	83.3
13	4	SHS100x100x10	388.3	4.62	9.64	88.0
14	5	SHS100x100x10	126.8	8.17	11.07	76.6

3.3 Availability check of decommissioned steel

The topside of an oil platform is commonly constructed by smaller modules which can be fabricated in the shipyard and transported to the site for further assembly. The steel components of one of the similar modules of decommissioned platform (Figure 3) has been considered for reuse purposes in this case study. The platform was operated in shallow water and the topside of it was supported by a bottom fixed jacket. Mainly the I type of cross sections are used for girders, transverse deck beams and stiffeners. Members with H type of cross sections have been used for supporting the decks and all the joints are welded. These types of members with H cross sections were selected for reusing in this apartment

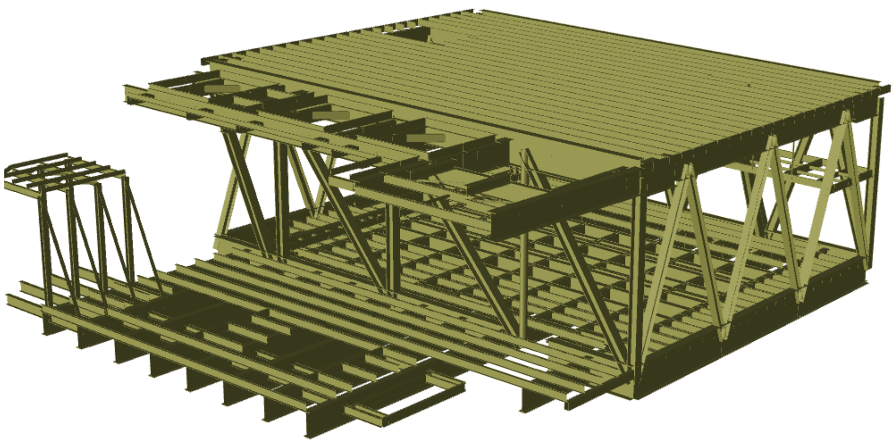

Figure 3. Decommissioned steel module of offshore donor platform

building based on the reduced capacities due to interaction of axial force and biaxial bending. The selected cross sections are universal columns (UC) 305×305×97, UC 356×406×235, UC 356×406×287 and UC 356×406×393. The original drawings and inspection/maintenance history of these members are available, while material documentations are not available. The material of the columns is grade 40EE and strengths are shown in British Standard BS 4360 [13]. The geometric details of the steel members and corresponding cross-sectional properties are given in the master's thesis of the first author [10]. The class of the cross-sections were classified based on guidelines given in Eurocode 3 [12] and results are shown in Table 3. Design resistance of the cross-sections for uniform compression ($N_{c,Rd}$) was calculated following the guidelines in Eurocode 3 as shown in Table 3.

Table 3. Material, geometrical properties and cross-section capacities of selected columns

	UC305x305x97	UC356x406x235	UC356x406x287	UC356x406x393
Steel grade	40EE	40EE	40EE	40EE
Maximum *t* (mm)	15.4	30.2	36.5	49.2
Yield strength (N/mm^2)	260	245	245	240
Flange class	2	1	1	1
Web class	1	1	1	1
Class of cross section	2	1	1	1
$N_{c,Rd}$ (N/mm^2)	3055.8	6976.7	8563.3	11442.3

3.4 Degradation status of the selected members

Accumulated fatigue damages of selected members are negligible since the selected members are extracted from a module of the topside. Therefore, corrosion is the main degradation mechanism which should be considered for the selected members. To take account intact to worst-case of corrosion degradation, three different uniform corrosion scenarios/cases were considered such as Case 1. no corrosion, Case 2. uniform corrosion along whole cross-section, and Case 3. Uniform corrosion along parts of the cross-section (which provides eccentricity of the centroid and additional bending moment). Considered three corrosion scenarios are shown in Figure 4.

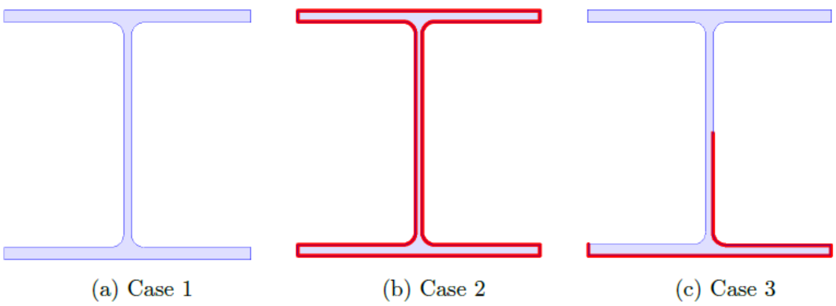

Figure 4. Corrosion cases

The service life of the considered module is 25 years (i.e. life span t =25 years). The coating life of the members is considered as 10 years (i.e t_{pt} = 10 years) for corrosion Case 2 and t_{pt} is assumed to be zero for Case 3 to simulate the worst case scenario. Time dependent thickness reduction due to uniform corrosion can be calculated using below function [14].

$$w(t) = A(t - t_{pt})^B \quad (3)$$

where $w(t)$ is the depth of corrosion in millimeters and t is age of the structure. The A and B are the parameters which depend on the corrosive environment and the type/grade of steel. The values for A and B are given in previously published article [14]. The corresponding cross sectional details and properties are shown in Table 4 for all 3 corrosion cases.

Table 4. Geometrical properties of the UC305x305x97with different corrosion cases

	Case 1	Case 2	Case 3
Depth of corrosion $w(t)$ (mm)	0	1.0	1.5
Cross section area (mm^2)	12345	10559	11462
Change of centroid e_z (mm)	0	0	11
Change of centroid e_y (mm)	0	0	2

3.5 Performance category assessment

The ranking of the performance categories (i.e operations of the reuse process) are determined based on the data and criteria description is presented in original article published by Technical Research Centre of Finland [5]. The feasibility values of ρ_i is selected to obtain the most conservative reusability index and the results are shown in Table 5.

Table 5. proposed ranking of the performance categories

Category	ρ_i	Comment
Deconstruction	0.5	Welded connections, moderately difficult access
Handling and manipulation	0.6	Manipulation by crane, forklift and small lifting devices
Separation and cleaning	0.4	Separation and cleaning using hand tools
Redesigning	0.8	Detailed drawings and maintenance history available
Repurposing	0.4	Some remanufacturing required
Modification	0.6	Columns are applicable for reuse without too much work
Quality check	0.4	Material documentation not available, require laboratory testing
Geometry check	0.8	Simple straightness testing using lasers

3.6 Life cycle assessment

One Click LCA [15] software was used for life cycle assessment (LCA) of this case study. The global warming potential (GWP) of this construction project was calculated by above software using environmental product declaration (EPD) according to Norwegian standard which provides the method for greenhouse gas calculations for buildings [16]. This method takes account every source of CO_2 emissions for building materials throughout their life cycle.

The GWP of the steel columns was assessed. The EPD of original RHS columns were taken from steel manufacturer, Tibnor [17]. The generic EPD for H-sections was utilized with reuse option/function for universal beams (UB) which were selected from decommissioned module. The total steel masses for both cases were given as an input to these assessments. It was assumed that only columns with SHS and RHS cross-sections replaced by UC 305×305×97. The circular columns in balconies with CHS 139.7×8 were not replaced with reuse columns as it is required to replace by similar shape and size due to aesthetic appearance/aspects. The transport distances were based on locations of Tibnor (i.e new steel manufacturer) and Aker Solution shipyard in Stord (i.e location of decommissioned offshore module) relative to the apartment building location at Sandefjord, Norway. It was assumed that mode of transport is onshore by lorries. The LCA results are shown in section 4.3.

4. Results

This section presents the capacities and utilization ratios of the selected members for reuse, results of reusability index and LCA. Comparison of capacities and design optimization with related discussion are made at the latter part of this section.

4.1 Capacities of reused columns

The RHS columns used in original design (Table 2) were replaced by selected UC columns in frame element model made by FEM-Design programme. The corresponding steel grade is also changed to 40 EE and ultimate limit state design checks were performed according to Eurocode 3 [12]. Additional bending moments due to eccentricities of corroded case 3 were imposed for ULS design checks. Hence, corresponding UR of the steel columns are obtained for the all the columns in each floor. Analysis results shows that UC305×305×97 cross section gives the highest URs and obtained URs for each degradation cases are shown in Table 6.

Table 6. Utilization ratios of selected UC305x305x97 columns with different corrosion cases

Column ID	Floor	N_{Ed} (kN)	$M_{y,Ed}$ (kNm)	$M_{z,Ed}$ (kNm)	Utilization ratio (UR) %		
					Case 1	Case 2	Case 3
1	2	594.4	12.81	3.56	33	42	40
2	2	850.1	18.21	0.56	38	49	47
3	2	729.0	0.79	5.49	39	36	34
4	2	697.3	0.90	4.87	27	34	32
5	2	438.4	1.64	7.79	19	24	22
6	2	595.9	1.48	13.83	28	35	32
7	3	429.3	17.84	17.46	29	33	32
8	3	607.5	11.33	14.95	31	38	35
9	3	504.8	2.43	5.93	21	26	25
10	3	474.4	1.19	4.79	19	24	23
11	3	443.1	1.22	12.86	22	27	25
12	4	273.8	8.14	11.85	18	21	19
13	4	388.3	4.62	9.64	19	23	22
14	5	126.8	8.17	11.07	12	14	12

4.2 Calculated reusability index

The reusability index was calculated for selected columns from equation (1) by following the guidelines given section 2. The proposed weighting factors in Table 1 and ranking values of performance category given in Table 5 were used to calculated final reusability index as shown the Table 7.

Table 7. Reusability index calculation

Category	ρ_i	w_i	$\rho_i\, w_i$
Deconstruction	0.5	0.25	0.125
Handling and manipulation	0.6	0.10	0.06
Separation and cleaning	0.4	0.10	0.04
Redesigning	0.8	0.10	0.08
Repurposing	0.4	0.05	0.02
Modification	0.6	0.05	0.03
Quality check	0.4	0.30	0.12
Geometry check	0.8	0.05	0.04
$r = \sum \rho_i\, w_i$			0.515

4.3 Life cycle assessment results

The LCA was performed as described in section 3.6. The input parameters of LCA and GWP results are shown in Table 8. Figure 5 shows the distributions of GWP for new and reused steel columns respectively.

Table 8. Input parameters and LCA results

Category	New steel	Reused steel
Mass (*kg*)	5220	14928
Assumed transport distance (*km*)	185	430
Global warming potential, GWP (*kgCO2*)	14838	667

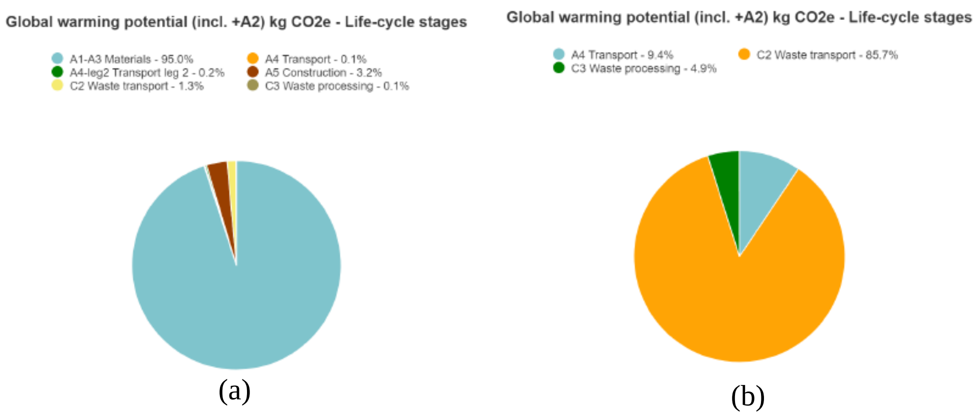

Figure 5. LCA results (a). GWP for original RHS columns, (b). GWP for reused UC305x305x97

5. Comparison and Discussions

Comparison of the results between new steel and reused steel applications are made in this section and related discussions are presented.

5.1 Design optimization

Utilization ratios of selected reuse columns in Table 6 (i.e max UR is 47%, whereas new steel shows max UR as 98.3%) shows that those columns have a more than sufficient capacity to withstand the loads. This indicates that considered decommissioned module of offshore topside is applicable for new buildings which are same size, and larger buildings than considered in this case study. The capacities of the degraded/corroded columns shows that remaining capacities are sufficient to withstand the load though there is possibility of some corrosion degradation of the reuse columns/members. The degraded columns should be treated and protected against development of further corrosion.

This case study results shows that selecting suitable columns from a larger pool of steel components from decommissioned oil platforms is beneficial in order to choose most suitable columns which gives higher UR. Design optimization can be achieved in this way and, leads to huge cost reduction than new steel. Alternatively, change of structural configuration/architecture (i.e conceptual design) can be done to suit the capacity of pre-used (reused) steel columns. The changes would include changing span length and height of columns, changing the load paths and etc which could change the modification performance category in the reusability index.

5.2 Feasibility/reusability

The reusability index (*r*) describes the degree of practicality/feasibility of reuse of decommissioned steel members for this case study. However, this always depends on the performance categories and weighting factors. The *r* for considered case study is 51.5% as shown in Table 7 and this hardly indicate a profitable reuse operation. The drawback should be identified and address to increase the reusability index. Low-scoring performance categories with corresponding largest weighting factors (i.e. deconstruction, quality checks and etc) are most potential for improvement.

5.3 Environmental and economic perspectives

Significant environmental benefits with regards to global warming potential (GWP) can be achieved when reuse the decommissioned steel components for this case study as shown in Table 8. More specifically, 5220 kg of new steel columns yields emission of 14838 kg of CO_2. The total mass of 14838 kg yields 667kg of CO_2. This provides GWP of 2.84 $kgCO_2/kg$ and 0.04 $kgCO_2/kg$ for new and reused steel respectively. The GWP associated to re-manufacturing and construction were neglected by the LCA software in this case study. The GWP associated with number of additional emissions in the reuse process such as decommissioning, dismantling, storage and etc, should be considered in LCA. Therefore, it would be beneficial to have both EPD, which specifically made for reused steel from offshore topsides and EPD, which took accounts all the emissions throughout all the service life of the new steel from production stage. It may be sensible to focus on the fact that emissions due to remelting during recycling process of the decommissioned steel can be omitted when reusing the steel.

Calculating cost benefits behind the reuse process is currently an impossible task as there is no marketplace for it. A full cost breakdown structure (CBS) should be created to determine the accurate cost for reuse steel in this case study by involving all the parties in the supply chain. Hence, cost and potential savings can be calculated.

6. Conclusions

An index has been introduced and modified in this paper to quantify the reusability of pre-used steel from offshore topside module to new building. A real-life case study was performed to observe the applicability and significance of the reuse process.

The case study results shows that reusability index is 51.5% which make room for improvement of the reuse process with regards to economical and sustainability aspects. The improvement can be achieved by changing the decommisioning process more industrialize and streamline the supply of the reused offshore steel for the building construction industry such as i) facilitate the shipyard to be able to de mounting the topsides in way the members are reusable afterwards, ii) incorporate stock list in the steel supply chain that specialize in the refurbishing process, and have capacity for quality and geometric checks, and iii) establish a competitive logistic network with storage and transportation capacities for reused steel. Therefore, it is beneficial to have above three facilities in companies which responsible for decommisioning activities and own the shipyards. This study concludes that decommissioned steel has a sufficient capacity for large number of building construction projects and there would be a market for reused offshore steel in building construction industry if above three changes are implemented.

Development of generalized guideline/framework for inspection and testing for remaining capacities of degraded/damaged members and development of EPD for reused offshore steel are recommended for future studies.

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