THE INFLUENCE OF A ROOF MOUNTED SMALL-SCALE HAWT ON HEADED STUDS FATIGUE RESISTANCE

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ABSTRACT

Installation of small-scale wind turbines in urban regions can gain higher energy efficiency, considering that energy production takes place at the place of its consumption. The aim of this work is to investigate effects of installation of a small-scale horizontal axis wind turbine (HAWT) on a roof structure of an existing building. This paper is focused on fatigue resistance of headed studs that are preinstalled in the building roof composite steel-concrete deck to ensure shear connection and that are indirectly dynamically loaded during wind turbine operation. Turbulent wind profiles with mean wind speeds from 3 m/s up to 15 m/s are generated and applied on the model of HAWT with 5 m rotor diameter using Ashes software package. Time-dependent forces and bending moments induced by wind turbine operation are applied on the composite roof deck model. Based on the time-history of transverse force in the composite steel-concrete beam and wind speed records during a year, fatigue cumulative damage of headed studs is calculated according to Eurocode. It is obtained that installation of HAWT do not significantly affect residual life of headed studs with reference to fatigue.

1. INTRODUCTION

Sustainable development principles lead to increased usage of renewable energy resources, as it is a wind energy. Considering the idea of high energy efficiency by producing and consuming electrical power at the same place, it is intended to install small-scale wind turbines in urban regions. However, due to the lack of free open areas in urban environment, the preferable solution is installation of small-scale wind turbines on building roofs.

A possible shortcoming of wind turbine mounting on the building's roof is related to increased vibrations that may affect human comfort and serviceability of equipment in a building [1]. However, another potential problem is related to the fatigue resistance of specific structural details of a building structure. Frequent stress fluctuations in construction elements caused by dynamic nature of wind loading and rotation of wind turbine blades, affect cumulative fatigue damage of certain details. Especially sensitive to fatigue damage are welded connections, as it is the connection between headed stud shear connectors and steel beams or profiled steel sheeting in steel-concrete composite buildings.

In this paper it is investigated how fatigue resistance of headed studs preinstalled in the roof steel-concrete composite beam is affected by installation of the small-scale horizontal axis wind turbine (HAWT) on the building roof. It is assumed that building is previously designed without an intention of installing wind turbine, which is mounted subsequently. The considered wind turbine is a small-scale HAWT with 5 m rotor diameter and 5 m tower height, that operates at wind speeds up to 15 m/s. HAWT model is developed using Ashes software package [2]. Calculation of fatigue damage accumulation factor is done according to EN 1993-1-9:2005 [3] and EN 1994-1-1:2004 [4].

2. METHODOLOGY

Model of small-scale HAWT with 5 m rotor diameter and 5 m tower height is developed using a multi-body analysis software package Ashes [2], that integrates finite element analysis (FEM) and blade element momentum theory (BEM). Model of small-scale HAWT is developed by scaling a standard NREL_5MW onshore wind turbine through dimensions scaling with factor 0.04 (Figure 1) [1]. However, as *wind turbine with local scaling of dimensions does not always give appropriate* *masses for different wind turbine parts, it was necessary to manually define* masses for wind turbine elements. *Mass of the support tower and RNA structure (rotor-nacelle assembly) in comparison to the mass of the whole wind turbine of* 553 kg *is approximately 50 % each*. The developed HAWT is a direct drive turbine without pitch control system *with rated power of 2.4 kW. It is assumed that wind turbine does not operate at wind speeds above 15 m/s.*

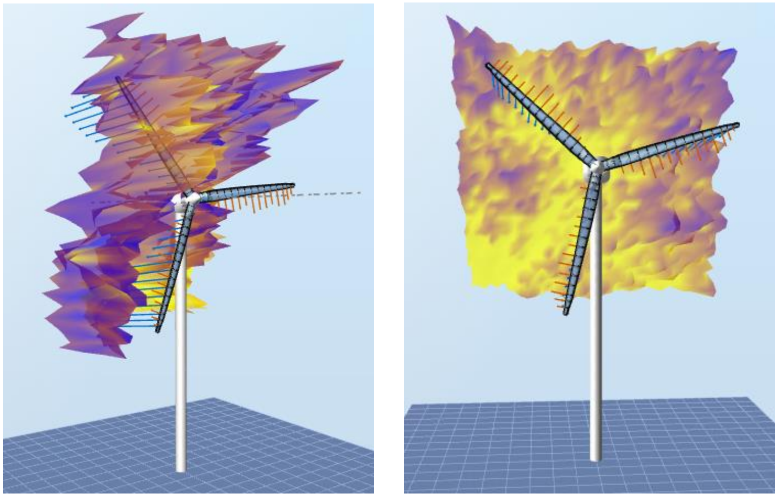

Figure 1. Model of the small-scale wind turbine and the tower in Ashes software.

Turbulent wind profile is generated in TurboSim module integrated in Ashes software [2]. In order to model spatial distribution, wind field is defined in certain number of grid points. The time history loading is generated for set values of mean wind speeds during time period of 60 seconds and applied on wind turbine model.

The obtained wind turbine support reactions due to applied wind loading of mean wind speeds from 3 to 15 m/s are presented on Figure 2. It is important to highlight that results presented in Figure 2 are filtrated from results of Ashes software in order to give proper graphical presentation, and that real data contain more fluctuations. However, wind turbine support reactions with real fluctuations are used for fatigue analysis of headed studs, in order to give realistic prediction of fatigue cumulative damage.

The time-history response of the composite roof beam due to dynamic loading generated by HAWT operation is analysed in Sofistik FE software [5]. The overall dimensions of the building roof are 24x24 m, as it is shown in Figure 3. Design of all elements is performed according to requirements given in EN 1994-1-1:2004 [4]. Steel-concrete deck is composed of 330 mm high steel I beams connected by shear connectors to the 160 mm thick concrete deck. Headed studs that connect steel beams and concrete deck are ductile shear connectors, which number provides partial shear connection, according to EN 1994-1-1:2004 [4]. The adopted headed stud's diameter is 16 mm and the distance between headed studs is 300 mm.

In order to investigate shear studs fatigue damage, HAWT position is assumed to be in the most unfavourable place, in the middle of the composite beam span, at the central position of the analysed roof structure, as presented in Figure 3.

Reaction loads induced by wind turbine operation (Figure 2) are applied on Sofistik model as time-histories of forces and bending moments. For investigation of headed studs fatigue damage, time period of 60 seconds of HAWT operation is taken into account. Headed studs' shear stress is calculated according to linear elastic theory, using the results of dynamic analysis performed in Sofistik. Shear stress results for applied wind loading of mean wind speeds of 3, 6, 9, 12 and 15 m/s during 60 seconds of HAWT operation are presented in Figure 4. For stress range counting, a rain flow method is performed.

The analyse of headed studs fatigue lifetime is based on a year record of wind speed for the site near the town of Vršac in Serbia [6]. Wind speed histogram obtained from the record is presented in Figure 5. As wind turbine operation is analysed for five different wind speeds, it is adopted that number of stress range cycles for certain wind speed corresponds to the frequency of that wind speed and lower wind speeds.

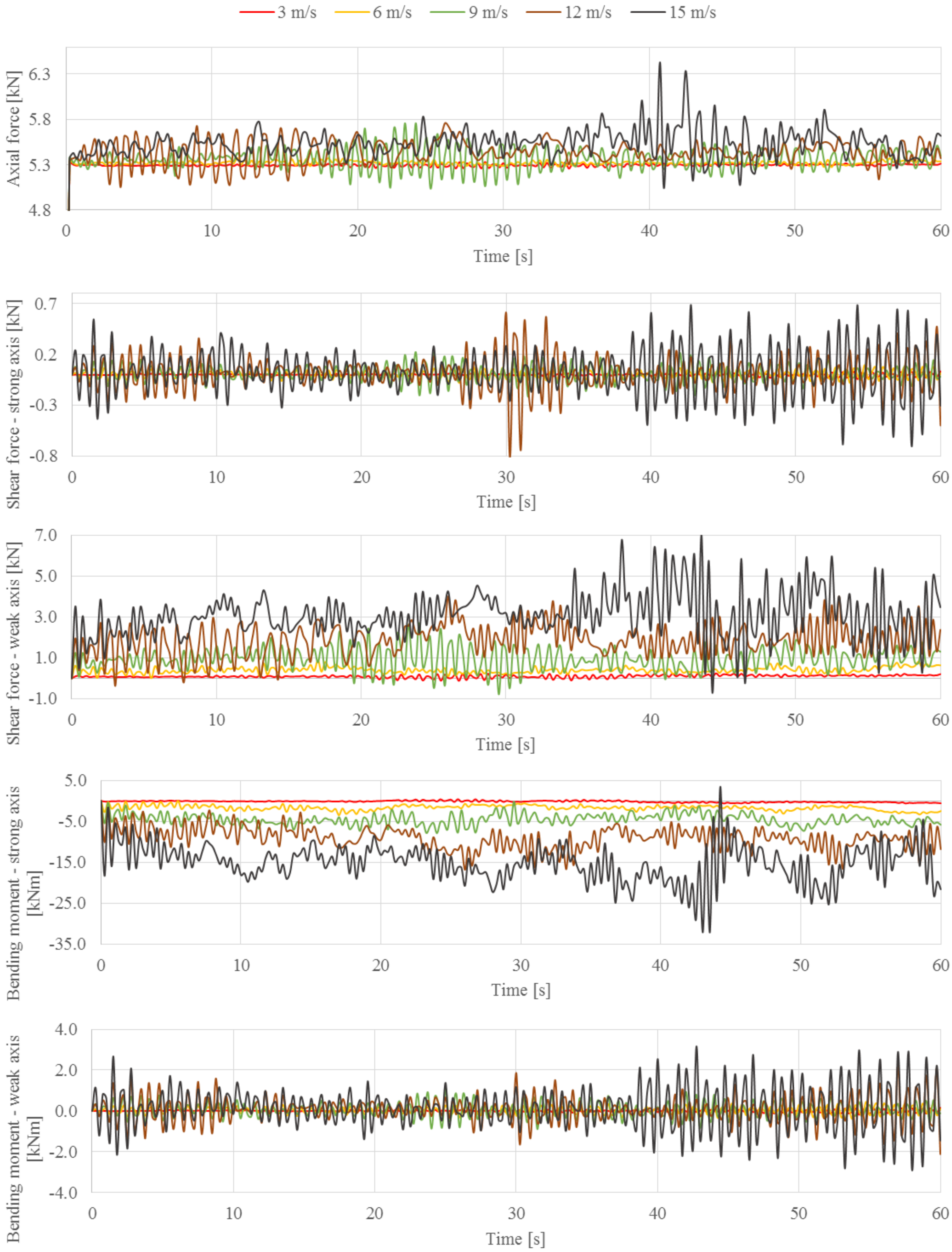

Figure 2. Time-history of wind turbine support reactions for different mean wind speeds.

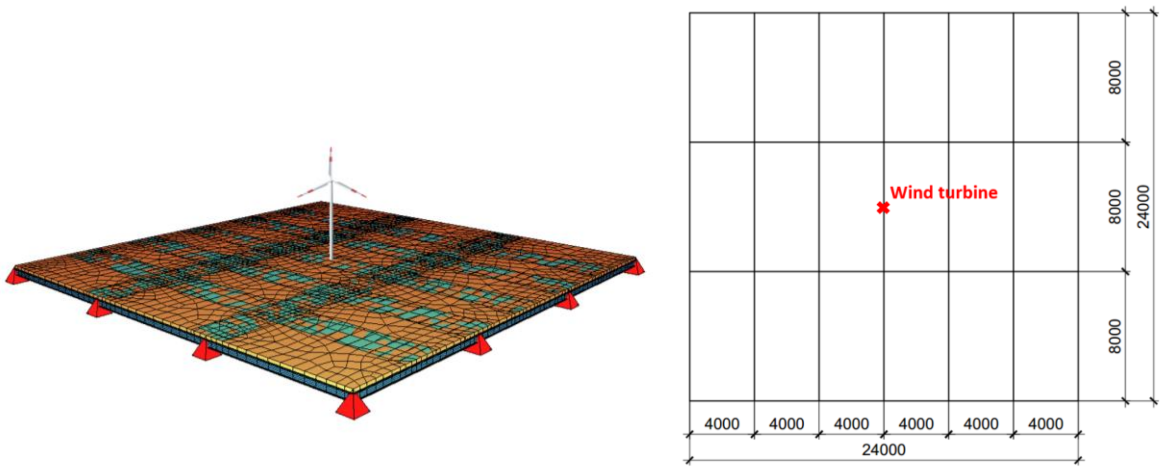

Figure 3. Layout of roof beams.

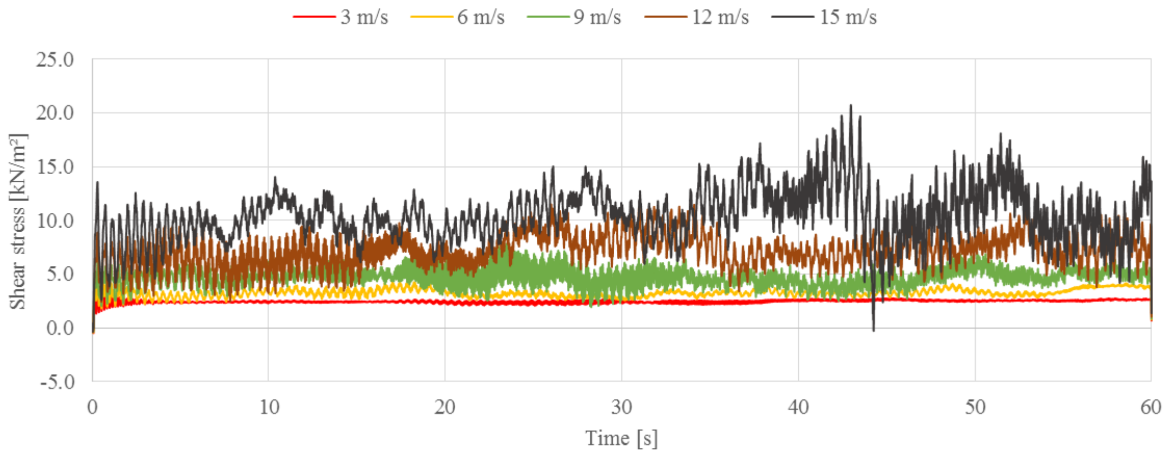

Figure 4. Time-history of shear stress in headed studs for different mean wind speeds.

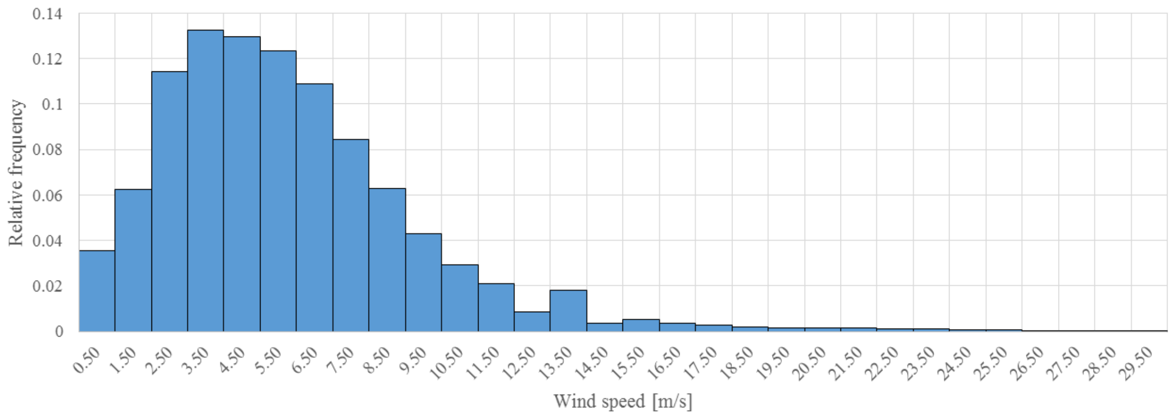

Figure 5. Wind speed histogram.

3. RESULTS

Taking into concern floor response during 60 seconds of wind profile application on the wind turbine and results of rain flow counting procedure, stress range histograms for each wind speed are obtained and presented in Figure 6.

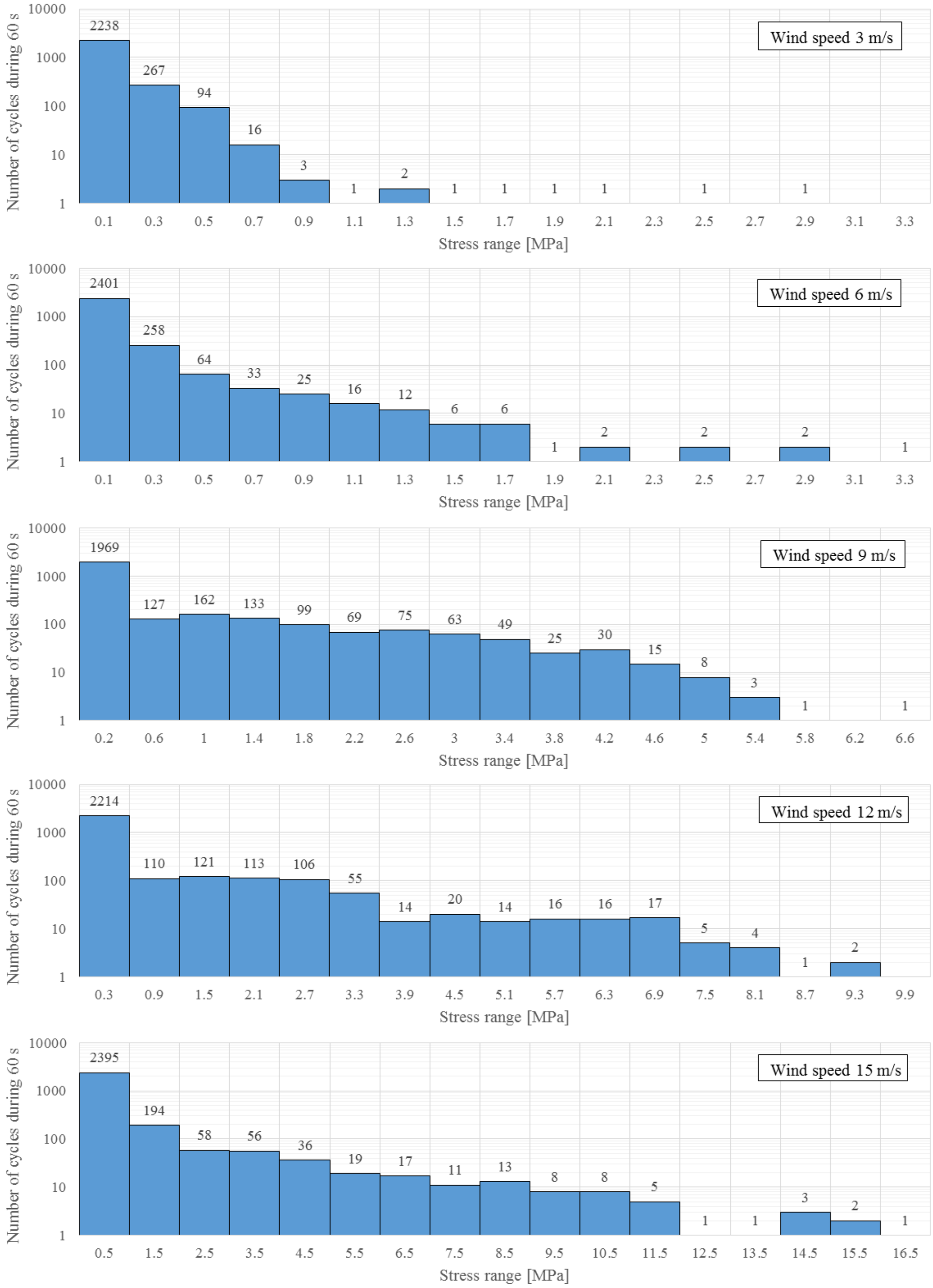

Figure 6. Stress range histograms for different mean wind speeds.

According to EN 1993-1-9 [3] and EN 1994-1-1 [4], accounting wind speed records and stress range histograms, damage accumulation factor for shear studs is calculated. The detail category of headed suds defined in EN 1994-1-1 is 90 MPa, while S-N curve has the slope 1:8 [4]. Adopted partial safety factors for fatigue strength and fatigue load are both 1. It is assumed that HAWT design life is 20 years. The

obtained damage factor equals $2.18 \cdot 10^{-6}$, that is much smaller than limiting value of 1. Therefore, the influence of the mounted wind turbine on fatigue life of headed studs preinstalled in the composite steel-concrete slab is very small.
The parameter study is performed by varying distance between shear studs. Results presenting damage accumulation factor are given in Table 1.

Table 1. Damage accumulation factor depending on distance between headed studs.

distance between headed studs [mm]	damage accumulation factor
300	$0.02 \cdot 10^{-4}$
400	$0.23 \cdot 10^{-4}$
500	$1.27 \cdot 10^{-4}$
600	$5.71 \cdot 10^{-4}$

Again, it could be noticed that fatigue damage due to wind turbine operation on the building roof is not remarkable. In the case of shorter distances between studs, shear stress in each stud is lower and therefore it is followed by smaller damage factor. Conversely, in the case of larger interspaces between headed studs, higher damage factors are obtained. However, all presented outcomes show that fatigue damage is negligible.
Additionally, the other possible failure on the connection of shear stud and beam flange, through the base material is tested. According to the time-history of direct stresses in the upper beam flange, detail category of 80 MPa and bilinear S-N curve with slopes 1:3 and 1:5 [3], damage accumulation factor is calculated. Adopted partial safety factors for fatigue strength and fatigue load are 1.15 and 1, respectively. The calculated damage factor equals 0, as all considered direct stress ranges are bellow cut-off limit and according to Eurocode [3] do not contribute to the fatigue damage.
The results lead to conclusion that fatigue failure generated by HAWT operation on the building roof could be neglected. Shear stress ranges to which shear studs are exposed as well as direct stress ranges in the base material, are very low and therefore do not significantly contribute to the cumulative damage.

4. CONCLUSION

Installation of a wind turbine on a roof of an existing building in urban environments requires consideration of dynamic loading on a structure, that had not been analysed during structure design. Wind turbine subsequent implementation could significantly affect the resistance of structural elements or serviceability of the structure. The influence of frequent stress fluctuations in construction elements on reduction of element's fatigue resistance due to installation of small-scale HAWT on the building roof is presented in this paper. The construction detail which is analysed is welded connection between headed studs and steel beam in a composite steel-concrete roof deck.
According to the results of the performed analysis, following conclusions could be stated:

- fatigue life of headed studs in a roof deck is satisfied for a HAWT design life of 20 years,
- damage accumulation factor is remarkably smaller than limiting value of 1, even in the case of longer distances between shear studs along composite steel-concrete beam,
- installation of small-scale HAWT on the roof deck of the existing building which is analysed in this paper does not affect life of headed studs and fatigue failure could be neglected. Also, in the case of different building structure geometry significant differences in fatigue damage results are not expected.

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