Non-destructive Examination of Loads in Regular and Self-locking Spiralock® Threads through Energy-resolved Neutron Imaging

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ABSTRACT: Energy-resolved neutron transmission imaging is utilised for in situ comparisons of strain distributions in fastened assemblies with regular and self-locking Spiralock® female threads. The strain maps measured within torqued steel bolts indicate that for a Spiralock® thread, the load is distributed over a larger section of the fastener, making this type of thread more suitable for fastening of assemblies subject to transverse vibrations.

KEY WORDS: Bragg edge analysis, neutron transmission imaging, non-destructive testing, self-locking threads, strain distribution

Introduction

A variety of specialised locking mechanisms is implemented in various systems subject to thermal, vibrational and environmental stresses. In some cases, regular checks and retightening of fasteners can be performed, alleviating the requirement for locking sustainability. However, in some specific cases where access to fasteners is impossible (e.g. in systems launched into space or other inaccessible locations), the reliability of an entire system may depend on the ability of fasteners to remain in their locked positions under different loads to maintain the integrity of the entire system. Spiralock® technology is one of those possible solutions for assemblies subject to extensive vibrational loads [1]. It utilises a modified female thread profile which features a 30° wedge ramp at the root of the thread (Figure 1). Standard male fasteners, which can be used with the Spiralock® female threads, spin freely until the clamp loading is applied. Upon loading, the tip of the male thread is pushed against the wedge ramp, creating a locking mechanism along the entire length of contact between the male fastener and the female thread (Figure 1). This locking substantially decreases the probability of the fastener to loosen under vibration [2–6]. The locking is reversible, and the same fastener and thread can be reused multiple times. It is claimed that the Spiralock® locking mechanism outperforms even regular all-metal locknuts and maintains the locked condition of the fastener all the way to the point when the fastener itself fails due to fatigue [1]. The torque required for the Spiralock® thread is typically 10 to 20% higher, due to the redirection of forces from the axial direction to a radial direction to create the locking of the fastener.

It is stated by the manufacturer that the Spiralock® threads have been tested extensively and indeed these threads were implemented on several NASA space missions, including the mass spectrometer instrumentation on the Huygens mission that landed on Saturn’s largest moon [7]. Although the improved performance of Spiralock® threads under transverse vibrational loads has been verified by direct vibrational testing, there is no published data known to the authors on the experimental confirmation of the hypothesised reason for the improved performance. It is assumed that the load distributions in the Spiralock threads extend over a larger fraction of the assembly and are distributed more uniformly, as shown in Figure 2. It is assumed that the improved stability under vibration loads is achieved due to the fact that a longer part of the fastener is loaded in the Spiralock® thread compared to the regular assembly configuration (Figure 2). Direct measurements of stress distributions within the fastened assembly are problematic without a priori knowledge on the mechanical properties (e.g. Young’s modulus) of some parts of the assembly, where some components may have varied strength and texture. However, the distribution of strain can be obtained directly by a non-destructive technique such as neutron diffraction or energy-resolved neutron imaging. No systematic in situ studies of strain distributions within Spiralock® threads have been published so far. The experimental study presented in this paper compares the strain distributions within standard steel fasteners installed in conventional and Spiralock® threads. The measured strain maps can be used for the comparison of the loads in the assemblies with respect to vibrational stability of the two thread systems.

A number of various testing techniques can be utilised to measure the in situ strain distributions of fasteners. Non-destructive testing techniques exploiting neutrons are often used for the studies of samples opaque to other more conventional methods, e.g. utilising X-rays. Neutron diffraction techniques have the unique capability to measure strain in relatively thick samples (e.g. >20 mm...
steel) due to their high degree of penetration into metals and the presence of Bragg scattering, which is sensitive to the lattice parameter of solid materials [8]. The conventional neutron diffraction methods with two 90-degree detectors either side of the incident beam measure two strain components at a time in a three-dimensional volume, determined by the size of the interrogating neutron beam, typically 1 mm³ or larger [9, 10]. In order to measure the distribution of strain components across a given area of a particular sample, multiple scans are usually performed. The alternative technique which measures neutron diffraction in a transmission mode has been developed recently, and it allows mapping strain in two dimensions with a few hundred micrometre spatial resolution across a ~3 x 3 cm² area, all in one measurement [11–16]. Thus, the strain distribution within the male fastener and the female thread can be obtained non-destructively with this technique with relatively high-spatial resolution. One of the limitations of this technique is the fact that the measured strain represents the averaged value integrated over the sample thickness, i.e. along the entire path of neutron travel within the sample. Thus, for the cylindrical geometry of our fastener samples, the radial and hoop strains are integrated through the thickness of the fastener and the female thread material. Previous experiments demonstrated that in some cases (e.g. in case of cylindrical symmetry), the individual strain components can still be extracted [17]. The fastened assembly studied in the present experiments is not exactly cylindrically symmetric, and only the core of the screw volume is subject to a two-dimensional strain field (far from the edge of fillets) or uniaxial stress fields. Therefore, the exact quantification of radial and hoop strains within the fastener assembly in our study is problematic and is not performed. However, the relative values of strain can still be imaged and compared for the regular and Spiralock® threads, indirectly demonstrating the differences in the load distributions for these two types of threads.

**Experimental Setup**

Two sets of male fastener/female thread samples were used in our experiments, each containing a pair of regular threads and a pair of Spiralock® threads (1/4 in – 20 tpi), drilled next to each other; four hardened steel bolts were used. A spacer bar with a through hole was fastened by these steel bolts to the bottom bar containing the threads. One sample contained an aluminium spacer and base bar with the threads (machinable multipurpose MIC6 cast aluminium, McMaster-Carr part #86825 K17), and the other consisted of a steel spacer and base plate (multipurpose 304 stainless steel, McMaster-Carr part #8992 K119). Standard commercial off-the-shelf drill bits were used to drill the regular and Spiralock® threads. For each sample, a pair of

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**Figure 1:** Schematic diagram of a Spiralock® thread with a 30° wedge introduced at the female part of the thread. Male fasteners with regular threads are used with Spiralock® female threads [1]

**Figure 2:** Schematic diagram comparing the radial load distributions estimated for the regular and Spiralock® threads [1]
bols was torqued to a given specification, and the other pair was inserted into the threads without any load. The second pair of bolts was used for the measurement of residual strains in the bolts and in the drilled plates, produced by the bolt manufacturing process. The bolts fastened to the regular thread were torqued to ~170 Lb-In, and the bolts in Spiralock® threads were torqued to 185 Lb-In for both samples. Two sets of measurements were conducted for each sample: one for the torqued pair of bolts and the other for the separate pair of un-torqued bolts. The through-beam thicknesses of the assemblies were ~20 mm for all samples. The photographs of the samples used in our experiments are shown in Figure 3.

The energy-resolved neutron imaging experiments were conducted on the ROTAX beamline facility at ISIS-pulsed neutron source, Rutherford Appleton Laboratory, UK. The short neutron pulses, produced with 50 Hz frequency, travelled to the detector installed at a distance of 15.82 m from the source. A neutron-counting detector with 28 × 28 mm² active area and 512 × 512 pixels readout was utilised in the present experiment [18, 19]. The neutrons in that detector are converted into electron pulses by the neutron-sensitive MCPs manufactured by Nova Scientific [20]. These electrons are subsequently registered by a 2 × 2 array of Timepix readout ASICs [21] capable of acquisition of ~1200 frames per second, with multiple neutrons detected in each frame. The position (with 55 μm accuracy) and arrival times (~0.5 μs accuracy) were measured with the detector for each registered neutron, with detection efficiency ~50% in the thermal range of neutron energies [22], used in the present study. The samples were mounted in front of the detector (~12 mm from the active area) in the direct path of the neutron beam. Multiple events were recorded for each readout frame of the detector, with five frame-readouts per individual neutron pulse implemented in order to reduce the detrimental effects of event overlaps in a single readout frame. The energy of each detected neutron was calculated from its time of flight according to the equation:

$$\lambda = \frac{h(T + \Delta T_0)}{mL},$$

where \(m\) is the mass of a neutron, \(L\) is the flight path, \(\Delta T_0\) is the time offset of the source trigger received by the data processing electronics and \(h\) is Planck’s constant. The parameters \(L\) and \(\Delta T_0\) were calibrated by fitting the measured transmission of a known material (Cu powder in

![Figure 3](image_url)

**Figure 3**: Photographs of the measured samples. (A) Aluminium plate with female threads and a spacer with through holes; (B) and (C) stainless steel base plate and spacer; and (D) hardened steel bolts (1/4 in – 20 tpi)

![Figure 4](image_url)

**Figure 4**: Calibration of experimental setup. (A) Transmission spectra measured for a copper powder. (B) The values for the flight path length and the time delay of the source trigger are obtained from the linear fit into measured Bragg edge wavelengths of copper powder obtained from the spectrum shown in figure (A)
this case) to the transmission calculated from a tabulated data set. Figure 4 shows the transmission of Cu powder which was measured for the calibration of parameter $L$. That powder sample is assumed to be in a stress-free state making it suitable for the experimental setup calibration. The sharp variations of the measured transmission at a set of neutron wavelengths specific to copper correspond to the so-called Bragg edges, which in turn correspond to interatomic distances of lattice planes with $(h,k,l)$ Miller indices [23] used for labelling in Figure 4A. The measured TOF values for the Bragg edges are plotted against tabulated wavelengths for these edges of copper in Figure 4B. The gaps in the measured transmission spectra seen in Figure 4A correspond to the readout dead times, with a minimum of 320 μs for the current version of the detector.

For each measurement, an energy-resolved neutron transmission data set was obtained, which consisted of several thousands of $512 \times 512$ images, each corresponding to a particular neutron wavelength. Thus, the neutron transmission spectrum was measured for each pixel of the data set, and the analysis of these spectra allowed reconstruction of strain distribution within the samples [15, 24, 25]. Each pixel of the resulting data set has a corresponding neutron transmission spectrum which can be analysed for the reconstruction of some structural properties of the sample. The novelty of the present experimental setup is its ability to record 262 144 transmission spectra, all in one measurement. To eliminate the influence of the neutron beam spectrum, i.e. the non-uniformity of the beam intensity and detector response, each data set was normalised by the data recorded with no sample installed in the beam (sample-in/sample-out normalisation). The acquisition time for each data set was several hours. It should be noted that the neutron spectrum of the ROTAX beamline is not optimised for imaging experiments: the neutron flux is substantially lower at the wavelengths best used for such analysis. New dedicated energy-resolved imaging facilities [26, 27], currently in construction and with expected beam intensities much higher at the wavelengths of interest, will allow much shorter acquisition times.

Figure 5: White-spectrum transmission images of steel bolts fastening a spacer to the base plate. Left bolt (regular female thread) is torqued to ~170 Lb-In, the right bolt (Spiralock® thread) torqued to 185 Lb-In. (A) Transmission image of the assembly with the base plate and the spacer manufactured from aluminium. (B) + (C) Transmission images for the assembly with the base plate and the spacer manufactured from stainless steel. (C) It shows the same data as (B) except for a change of the display contrast, in order to visualise the threads as steel base has larger absorption than aluminium in sample (A). (C) The darker areas in the thread are due to attenuation by oil, which had been left on the bolt before fastening. The numbers indicate the areas for which spectra are shown in Figures 7 and 8.
Results and Discussion

The conventional white-spectrum neutron radiographies of both of the aluminium- and steel-base samples, with bolts torqued, are shown in Figures 5 and 6. The low attenuation of aluminium does not allow for the visualisation of the contact surfaces between the base thread and the bolt in Figure 5A, but it is clearly visible for the steel base in Figure 5C. The unique capability of thermal neutrons to penetrate a relatively thick steel sample (~11 mm) enables in situ imaging of the contact configuration for both threads. In addition, the oil redistribution within the interface between the bolt and the base thread can also be imaged with neutron radiography, as demonstrated in Figure 6 for the regular thread shown on the left. In the same way, neutron imaging can be used to investigate the distribution of a locking compound in case it is introduced into the gap between the bolt and the thread. The point contacts between the thread tips and the 30° wedge of the Spiralock® thread are clearly visible in Figure 6B, even though our experimental setup was at the limit of the required spatial resolution to a point where image blurring due to beam divergence may affect the extends of the observed contact points.

Reconstruction of strain distribution through Bragg edge analysis

In the case of polycrystalline materials, the presence of sharp steps in neutron transmission at certain wavelengths enables reconstruction of lattice parameters from the measured spectrum. The wavelength for which transmission exhibits such an edge corresponds to a 180-degree diffraction of neutrons by a set of crystallographic planes, labelled by a Miller index \((h,k,l)\), which are perpendicular to the incident neutrons and for which the interplanar distance \(d\) is half the wavelength, according to Bragg’s law. The corresponding step in the transmission spectrum is thus called \((h,k,l)\) Bragg edge. The sharpness of these Bragg edges depends on the resolution function of the instrument and on the microstructure properties of the polycrystalline sample. In general, the analysis of an entire transmission spectrum, using for example Rietveld fitting methods [28, 29], can reveal various microstructure parameters. The wavelength of the Bragg edge, in particular, can be used to measure the strain value from the equation:

\[
\text{Strain} = \frac{d}{\lambda} \sin \theta
\]

Figure 6: Same as Figure 5(C), zoomed into the interface between the bolt and female thread of the steel base plate. (A) The surface contact between the bolt and the regular female thread is clearly visible. (B) The point contact between the bolt thread crest and the Spiralock® thread is visible as imaged in situ through the entire thickness of steel base material.

Figure 7: Neutron transmission spectra measured for different areas of the sample with the aluminium base; see area labels in Figure 5 (A). The Bragg edges are labelled with Miller indices.
\[ \varepsilon = (\lambda - \lambda_0)/\lambda_0 \]  

providing the unstrained Bragg edge position \( \lambda_0 \) is known for the \((h,k,l)\) edge used in the analysis [11–16,29–32]. There are various methods of obtaining the unstrained edge position value, often referred to as ‘\( d_0 \)’, related to the measured Bragg edge position \( \lambda_0 \) through the Bragg’s law equation for 180-degree diffraction:

\[ \lambda_0 = 2d_0\sin\frac{\pi}{2}. \]  

An accurate determination of unstressed and texture-free lattice parameter \( d_0 \) is crucial for the accuracy of measured strain values. There are various methods used for the measurement of this parameter, among which are the measurement of lattice parameter for a texture-free powder, use of annealing and strain relieve grooves.

**Figure 8:** Neutron transmission spectra measured for different areas of sample with steel base; see area labels in Figure 5(C). The Bragg edges are labelled with Miller indices.

**Figure 9:** Measured and fitted (110) Bragg edge transmission spectrum of the steel bolt head. The fit parameters are schematically shown on the graph (except for the parameter associated with the asymmetry of the Bragg function related to the shape of the neutron pulse). By fitting an analytical function, the centre of the Bragg edge is recovered with precision much higher than the width of the edge itself. The instrument width is determined by the source moderation process.

**Figure 10:** Strain maps measured for the bcc steel bolts torqued to 170 and 185 Lb-In into regular and Spiralock® threads, respectively. The strain values are integrated along the neutron travel path (normal to the images shown here). Reconstruction of strain for two Bragg edges is shown. The \( \lambda_0 \) value was assumed to be the value measured at the bolt head.
and many others. In the present work, the exact value of $d_0$ parameter for the screw and the base part of the assembly was not available, and thus, only the relative strain distribution was measured. The $d_0$ ($\lambda_0 = 2d_0$) value was chosen somewhat arbitrarily as the Bragg edge wavelength where the sample is expected to exhibit no residual strain values – in the area of the bolt head (for the strain reconstruction within the bolts) and away from the drilled hole area for the spacer and the threaded area of the base bar. Therefore, the quantified strain values reported in this paper are used for the relative comparison of strain distributions within the measured fastener assemblies. Thus, these maps can be used for the evaluation of the uniformity and the extent of the strain caused by the fastener torqueing in the two assemblies.

The transmission spectra measured for the different areas of the samples are shown in Figures 7 and 8 with the Al base and steel base samples, respectively. The Al base, steel bolts (body-centred cubic structure - bcc) and steel base (face-centred cubic structure – fcc) exhibit edges at different wavelengths. It is this phase sensitivity which allows simultaneous determination of strain components for different phase components in one measurement. With sufficient wavelength resolution, as provided on a pulsed neutron source, the (110) edge position of the steel bolt, for example, can be analysed independently of the (111) edge of the fcc steel base plate, despite the fact that neutron transmission is integrated through the entire sample.

The accuracy of strain reconstruction from the Bragg edge analysis depends on how precisely the Bragg edge wavelength is measured. The width of the measured Bragg edge is determined by both the sample microstructure and by the width of the initial neutron pulse at a given wavelength. The latter pulse width is ~50 $\mu$s on the ROTAX beamline in the 3–4 Å wavelength range used in our analysis. This corresponds to $\Delta \lambda / \lambda \approx 0.3\%$, or 3000 microstrain. However, the accuracy of strain reconstruction can be improved by fitting an analytical

![Figure 11: Strain maps reconstructed for the fcc steel base and the spacer (the latter only in the area outside of the bolts). Integrated strain values across the entire sample are measured here. The resolution of our technique is not sufficient to measure the local strain values next to the crest of the male fastener, as shown in Figure 2 for the expected load distribution.](image)

Examination of Loads in Regular and Self-locking Spiralock® Threads: A. S. Tremsin et al.
function to the measured Bragg edge spectra [11–16, 29–32], allowing the accuracy to be better than ~100 microstrain in some cases, corresponding to an energy resolution of $\Delta \lambda / \lambda \sim 0.01\%$. This corresponds to fitting Bragg peak profiles in a powder diffraction analysis. Figure 9 shows a typical measured Bragg edge with a fitted seven-parameter function:

$$\text{Tr}(\lambda) = C_1 + K_1(\lambda - \lambda_0) + (C_2 + (K_2 - K_1)(\lambda - \lambda_0))$$

$$\times \frac{1}{2} \left( \text{erfc}\left( \frac{\lambda_0 - \lambda}{\sqrt{2}\sigma} \right) - \exp\left( \frac{\lambda_0 - \lambda}{\tau} + \frac{\sigma^2}{2\tau^2} \right) \text{erfc}\left( \frac{\lambda_0 - \lambda}{\sqrt{2}\sigma} + \frac{\sigma}{\tau} \right) \right),$$

which was used for the analysis of strain distributions across the samples, where $\lambda_0$ is the edge position, $\sigma$ and $\tau$ are the symmetric and asymmetric broadenings of the edge and $C_1$, $C_2$, $K_1$ and $K_2$ are constants. Neutron counting statistics measured in our experiment in each $55 \times 55 \mu m^2$ pixel and each $5.12 \mu s$ time bin was not sufficient for an accurate analysis of the Bragg edge position, and as in previous studies [15, 16, 24], we combined neutron counts from several neighbouring pixels (typically over ~0.5–1 mm area) into one spectrum before the fitting was performed. This process was repeated for all pixels of a data set thus enabling reconstruction of the averaged Bragg edge position for each $55 \mu m$ pixel.

**Measured strain distribution**

The 30-degree edge introduced by Spiralock® threads is expected to lead to a more uniform distribution of loads compared to loads in a regular thread, as schematically shown in Figure 2. As mentioned earlier, our experiments allow measurements of strain values integrated over the entire thickness of the sample, although independently for the steel bolts and the female thread material around it, as they are manufactured from different materials and exhibit Bragg edges at different wavelengths. In our analysis, we first obtained strain maps for different Bragg edges, as shown in Figures 10 and 11 for the steel bolts and steel base, respectively. The resulting strain distributions averaged over several edges are shown in Figures 12 and 13 for loaded and non-loaded bolts, respectively. There is a substantial difference in the measured strain distribution within the bolts between the regular and Spiralock® threads. The strain in the latter case is more evenly distributed across the length of the bolt section engaged with the female threads, gradually recovering to the unstrained values towards the end of the bolt where it is not engaged with the female threads due to a smaller diameter of the bolt. The cross sections through the measured strain maps of the bolts, Figure 14, demonstrate the differences in the measured strain values. The averaged strain of the base material and

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**Figure 12:** Measured strain maps across the steel assembly with torqued bolts. The strain values are integrated through the thickness of the sample and are averaged over the strain values for several Bragg edges shown in Figures 10 and 11: bcc bolts are averaged over (211) and (110) edges; steel base and spacer values are averaged over (111), (200), (220) and (311) edges. The dashed rectangles indicate the area for the cross section across the strain map shown in Figure 14.

**Figure 13:** Same as Figure 12, except measured for the bolts which are not torqued. A separate sample with similar but different bolts and base/spacer is measured, not the same sample as in Figure 12. The residual strain values are seen for the hardened steel bolts, but on much smaller scale compared to the torqued configuration.
the spacer shown in Figure 13 do not substantially deviate from the baseline zero values due to the limitation of our technique integrating through the entire thickness of the sample.

The same measurement performed for the sample with the aluminium spacer, and base materials did not show an increase in strain values in the bolts at the position of the first thread (Figure 15). The softness of aluminium most likely led to plastic deformation of the aluminium threads as the bolts were torqued to the same values as in case of steel. The plastic deformation of base threads, we believe, resulted in a more uniform distribution of measured strain values with lower absolute values.

Figure 14: Cross sections through the measured strain maps for the areas shown in Figures 12, 13 and 15. (A) Cross sections through the strain map of bolts torqued to a steel base with female threads (dashed rectangles of Figure 12). (B) Cross sections through the strain map of un-torqued bolts in a steel base, for the areas shown in Figure 13. (C) Cross sections through the strain map of steel bolts torqued into female threads in an aluminium base (Figure 15)

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Conclusions

Our experiments demonstrate that energy-resolved neutron transmission imaging provides information on the phase-separated strain distributions within metal structures in situ. Only strains integrated over the neutron path within the sample can be measured with this technique. In some specific cases, the individual strain components can still be reconstructed with a priori information about the sample, as demonstrated previously [17]. The spatial resolution of this technique can be a few hundred micrometres as it is currently limited by neutron counting statistics (determined by image integration times and the neutron fluxes at pulsed neutron sources). With the expected increase of the neutron flux at new neutron imaging facilities, the spatial resolution may be improved to the limit of our current detection system with 55 × 55 μm² pixels. Although this is inferior to the spatial resolutions of other methods, e.g. X-ray techniques, where spatial resolution reached nanometre scales [33], the unique possibility of neutrons to penetrate relatively thick samples can be attractive for some applications.
The strain maps measured simultaneously for the samples with regular and Spiralock® threads confirm the formation of a more uniform strain distribution within the Spiralock® threads, extending the areas where the bolts are engaged with the thread of the base material. In comparison, only a few thread loops are responsible for most of the fastener locking for the regular threads. The extended engagement range of the locked thread makes the Spiralock® threads acceptable for larger vibrational loading compared to the regular threads. It is this locking which makes Spiralock® threads attractive for many applications where the fasteners have to preserve their locked state in mechanically harsh environments with no access for periodic fastener servicing.

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