

Stiffness-based assessment of cyclic degradation in steel girders with sinusoidally corrugated webs

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ABSTRACT

Cyclic loading may progressively degrade the global structural response of thin-walled steel members before final failure becomes apparent. This study examines that process in full-scale steel girders with sinusoidally corrugated webs using a stiffness-based approach derived from load-displacement loops. The stiffness parameter K_i is used together with the N_{init} criterion, defined by a persistent decrease relative to the reference stiffness K_0 , to identify the onset of measurable degradation in global terms. To complement this diagnostic framework, the observed stiffness histories are also expressed in a normalized two-stage form using $\eta_K = K_i/K_0$ and $n = N/N_{\text{fail}}$. The method is applied to an experimental programme including a reference girder, girders subjected to cyclic loading until failure, and girders tested statically after prior fatigue loading. The results show that the global stiffness remains nearly constant during most of fatigue life and then decreases rapidly in the final stage preceding failure. The identified N_{init} consistently precedes N_{fail} , indicating an intermediate stage between apparently stable response and final failure and reflecting the stage at which local degradation begins to produce measurable consequences for the global response. The normalized representation captures the main features of the degradation histories and provides a compact comparative and interpretative description of degradation development. The identified degradation state also supports interpretation of the subsequent ultimate response, including reduced load-carrying capacity and possible changes in the governing failure mechanism.

Keywords: cyclic loading, stiffness degradation, damage initiation, normalized degradation history, steel girders, thin-walled structures.

INTRODUCTION

Steel plate girders are among the primary load-bearing members used in engineering structures. In the drive to reduce self-weight, their webs are usually designed as slender plates, which increases susceptibility to local instability under shear, bending, or combined action. In conventional solutions, strength and stability requirements are met either by increasing the web thickness or by using transverse stiffeners, both of which increase fabrication effort and cost [1,2].

An alternative is provided by corrugated-web girders, in which the corrugation acts as an ‘integrated stiffening system’, enabling high shear stiffness to be achieved while maintaining a small

plate thickness [3]. Such solutions are widely used, for example, in bridge systems and crane girders, where variable and repeatedly applied loads predominate [4–8]. In practice, different corrugation profiles are used (e.g., trapezoidal and sinusoidal), which affects the distribution of local stiffness and the nature of stress concentrations in connection details.

In structures subjected to cyclic loading, fatigue damage is a key issue. In girders with corrugated webs, the web-to-flange connection detail differs from a conventional straight joint: the weld path is curvilinear, and the changing corrugation geometry promotes elevated stress concentration and sensitivity to fabrication quality. Early studies already indicated that corrugation may alter

fatigue life compared with traditional solutions [9,10]. Subsequent investigations, mostly concerned with trapezoidal webs, identified typical crack-initiation locations (including the web-to-flange weld region and the fold-transition zones) and demonstrated the significant influence of corrugation geometry, bend radii, and weld details on stress concentration and fatigue life [11–21].

It should be noted, however, that much of the available research focuses on fatigue life itself and on the assessment of details within the S-N framework, whereas the influence of loading history on residual load-carrying capacity and on a possible change in the governing ultimate mechanism after a fatigue service period has received much less attention. This issue is particularly important for girders with slender cross-sections, in which both a local mechanism (e.g., web instability in the shear-force zone) and a global mechanism (e.g., lateral-torsional buckling, LTB) may develop at the ultimate limit state [22–26]. For sinusoidal webs, owing to their continuous curvature and larger bend radii, different stress-concentration conditions and interactions with local stiffening may be expected than in trapezoidal solutions, which limits the direct transfer of conclusions from the existing literature. This observation is also consistent with recent numerical work on steel beams with sinusoidal webs, which indicates that their response should be interpreted with explicit regard to sinusoidal-web geometry rather than by direct analogy with other corrugation forms [27]. Comparatively less attention has been devoted to sinusoidally corrugated webs, especially in full-scale tests combining cyclic loading, stiffness degradation, and the subsequent assessment of residual load-carrying capacity. This creates a gap between detail-oriented fatigue evaluation and the broader structural interpretation of how cyclic damage affects the response and failure of the whole girder.

The present study examines the onset of persistent degradation of structural response in full-scale girders with sinusoidally corrugated webs on the basis of the stiffness parameter K_i and the N_{init} criterion. To complement this diagnostic perspective, the observed stiffness histories are also expressed in a normalized two-stage form, enabling a compact comparative and interpretative representation of degradation development under cyclic loading. The study further considers how the identified degradation is manifested in the subsequent ultimate response, including

ultimate load-carrying capacity and the governing failure mechanism.

In contrast to detail-oriented fatigue assessment based primarily on crack initiation, stress concentration, or S-N relationships, the present study is focused on the stage at which local degradation begins to produce measurable consequences in the response of the entire member. For full-scale girders with sinusoidally corrugated webs, this issue is particularly important because the structural response may remain apparently stable for a long part of fatigue life, while the final stage of degradation develops over a comparatively short interval before failure. The main novelty of the paper therefore lies in the use of the stiffness parameter K_i , derived from load-displacement loops, together with the N_{init} criterion, as a global framework for identifying the onset of persistent degradation, and in linking this framework with a normalized two-stage representation of degradation development and with the subsequent ultimate response.

TEST PROGRAMME

General information

The experimental programme comprised five full-scale steel girders with sinusoidally corrugated webs, identical in geometry, fabricated from the same material, and tested under the same four-point bending arrangement [28].

The test programme comprised three stages. In the first stage, one test girder (TG1) was tested under static loading to failure in order to establish a reference for the assessment of ultimate load-carrying capacity and for the interpretation of response changes in members with a prior history of cyclic loading. In the second stage, two test girders (TG2 and TG3) were subjected to cyclic loading until failure, enabling analysis of the $K_i(N)$ evolution, identification of N_{init} , and comparison with the corresponding number of cycles to failure, N_{fail} . In the third and final stage, two additional test girders (TG4 and TG5) were first exposed to cyclic loading insufficient to cause failure and were then tested statically to failure, thereby allowing evaluation of how the previously identified global degradation was manifested in the subsequent ultimate response. Owing to the limited number of full-scale tests, the present study should be understood as a physically

consistent experimental series rather than as a statistically exhaustive basis for generalized quantitative prediction.

Test girders and material

The study involved single-span steel I-girders with parallel flanges and sinusoidally corrugated webs. Each girder had an overall length of 6510 mm, a calculated length of 6045 mm, a total depth of 540 mm, flanges 200 mm wide and 20 mm thick, and a 3 mm thick corrugated web with a web depth of 500 mm. The sinusoidal corrugation was characterized by a wavelength of 155 mm, an amplitude of 21.5 mm, a wave height of 43 mm, and a developed wavelength of 178 mm. In the present study, the sinusoidal-web geometry was defined by these parameters and by the corresponding geometric notation shown in Figure 1; owing to the continuously varying curvature of the sinusoidal profile, no single constant radius of curvature was adopted as an independent descriptive parameter.

In the support zones, double-sided transverse stiffeners extending over the full web height were provided, whereas in the load-application zones double-sided transverse stiffeners of partial height, approximately three-quarters of the web height, were used. The transverse stiffeners were 12 mm thick and 98 mm wide. Their role was to ensure proper transfer of concentrated forces, reduce local stress concentration, and limit the risk of premature fatigue-crack initiation near the

lower flange connection. The test girders were manufactured on an automated production line [29,30]. The web-to-flange connection was made with a continuous single-sided fillet weld having a variable throat thickness in the range 3.0–5.0 mm. The adopted technology ensured high repeatability of geometry and fabrication quality, thereby limiting the influence of manufacturing imperfections on the test results. Figure 2 shows a representative completed test girder.

All test girders were fabricated from S355 structural steel. Because cold forming of the corrugated web plate may modify the mechanical properties of the steel, additional tensile tests were carried out after completion of the test programme on material sampled from the web and the flanges in accordance with [31]. On this basis, the basic material parameters were determined, namely the ultimate tensile strength f_u , the yield strength f_y , and the modulus of elasticity E . The values are listed in Table 1.

The results confirmed similar mechanical properties for the web and flange materials, although the web material exhibited slightly lower f_y and f_u values. This difference may be attributed to the corrugation-forming process and to the natural scatter of material properties.

No direct measurements of welding residual stresses or out-of-plane web deformations were performed. It was therefore assumed that residual stresses and imperfections formed part of the initial ‘as-fabricated’ condition of the girders, and

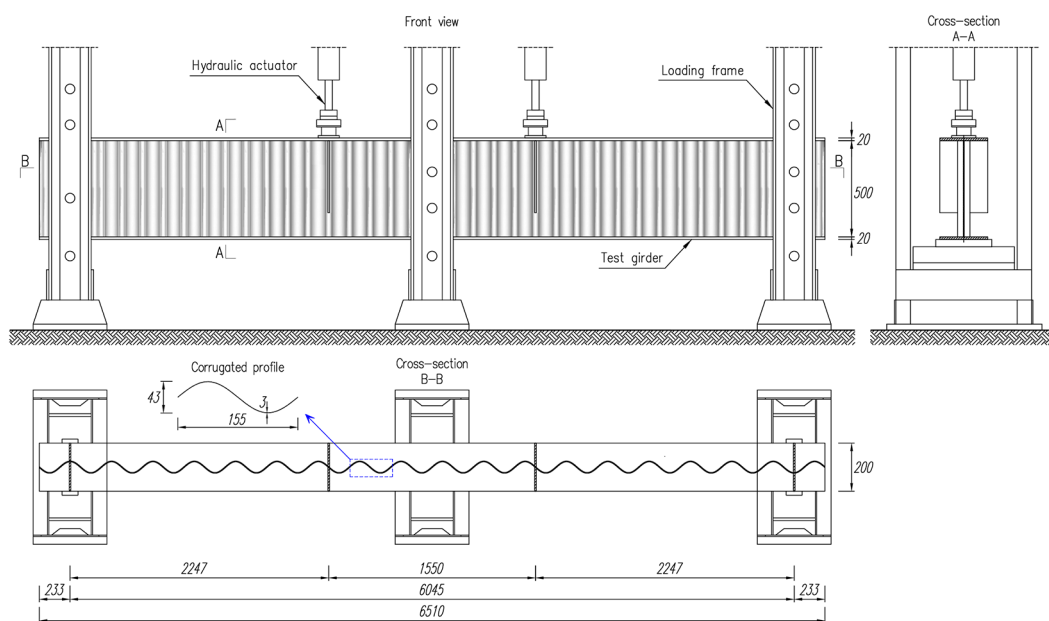


Figure 1. Geometric notation of the test girders (units: mm)



Figure 2. View of the test girder

Table 1. Mechanical properties of the steel used in the test girders

Location	E	f_y	f_u	f_y/f_u
	[GPa]	[MPa]	[MPa]	[-]
Corrugated web	207	370	506	0.73
Flange	209	379	514	0.74

that their influence was inherently included in the recorded experimental response.

Measured values and loading programme

During the tests, forces, global displacements, and strains at selected points of the girders were recorded. Of primary importance were the signals required to determine the global stiffness parameter K_i from the load-displacement loop, namely the force values and corresponding displacements at the $F_{\min}$ and $F_{\max}$ levels in successive load cycles. These data formed the basis for tracking degradation of the structural response as a function of the number of cycles N .

Local strain measurements and visual observations were treated as auxiliary information used to interpret the moment of damage initiation and to assess the agreement between the global signal and local degradation symptoms. Their role was to validate the adopted global criterion. The locations of the linear displacement transducers and strain gauges are shown in Figure 3.

The applied force was measured by means of a load cell integrated with the hydraulic actuator. Global displacements were recorded using LVDTs mounted on the underside of the bottom flange directly beneath each applied force. Strain gauges were installed in zones of expected stress

concentration, including the web-to-flange connection, the load-introduction region near the transverse stiffeners, and the midspan region within the constant-bending-moment zone. In addition, hot-spot measurement points were arranged in the web-to-flange detail in order to provide supplementary information on the local response of the welded connection.

In the longitudinal direction, the two A–A sections were located approximately 200 mm in front of the load-application points, whereas the B–B section was located at midspan. Accordingly, the principal displacement measurements were taken in the regions directly associated with the applied concentrated loads, while the strain measurements covered both the shear zone and the constant-moment region.

The tests were carried out on a full-scale four-point bending test stand under controlled force input. The girders were tested as single-span simply supported members. The support arrangement allowed free rotation of the cross-sections and did not provide additional torsional restraint, so that the natural structural response of the girder, including possible lateral-torsional buckling, could develop. Loads were introduced as concentrated forces applied to the top flange by means of hydraulic actuators. In order to reduce local stress concentration at the load-introduction points,

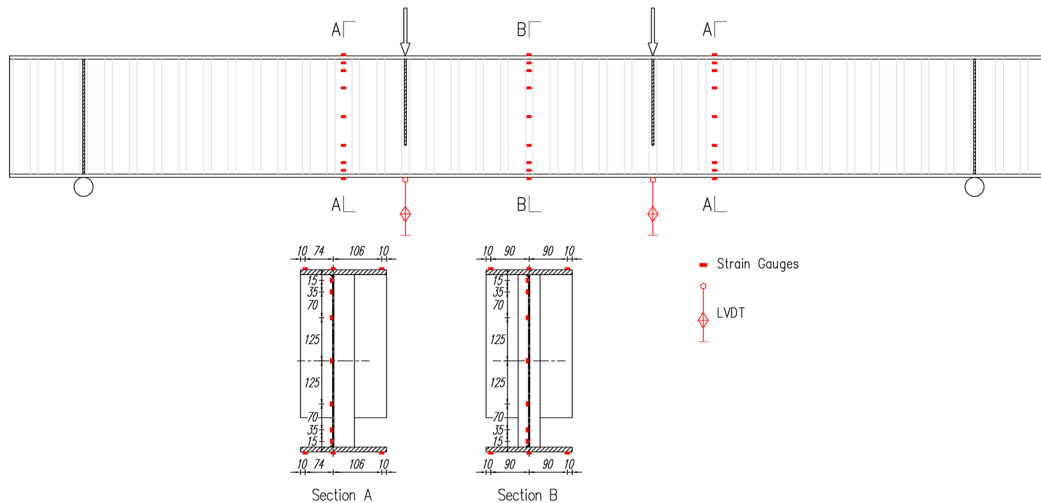


Figure 3. Arrangement of displacement transducers and strain gauges (units: mm)

steel distribution plates were used to transfer the load more uniformly to the girder.

In the cyclic tests, force-controlled loading was applied with a constant minimum value of $F_{\min} = 10$ kN and different $F_{\max}$ values depending on the programme adopted for a given girder. For test girder TG2, the range 10–260 kN was used, whereas for test girder TG3 a two-stage loading programme was applied: 10–130 kN up to 2.0×10^6 cycles, followed by 10–195 kN until failure. In the tests preceding residual load-carrying capacity assessment, the adopted ranges were 10–260 kN for test girder TG4 and 10–195 kN for test girder TG5. The loading frequency was 2 Hz. This loading frequency ensured stable signal acquisition while limiting the influence of dynamic effects on the global response evaluation. Under this test configuration, the global response could be treated as quasi-static for the purpose of determining K_i from the displacement values corresponding to the prescribed load levels within a cycle.

During the static tests, the reference girder (TG1) was subjected to monotonically increasing load until failure. The same procedure was subsequently carried out for test girders TG4 and TG5 after completion of the preliminary cyclic-loading stage. Throughout the static tests, the load–displacement response was recorded, and the evolution of strains and damage in the critical structural zones was monitored. The results formed the basis for comparing the ultimate load-carrying capacity of the reference girder with that of the girders with a prior cyclic-loading history.

GLOBAL STIFFNESS PARAMETER K_i AND IDENTIFICATION OF DAMAGE INITIATION

Definition of the K_i parameter and assumptions of the global analysis

In the classical description of fatigue tests, the basic comparative parameter is the number of cycles to failure N_{fail} . Such a description does not, however, capture the moment at which degradation of the member becomes measurable in terms of the global structural response while still preceding final failure. To quantify changes in the global structural response during cyclic loading, the stiffness parameter K_i was introduced for the i -th cycle on the basis of the recorded load-displacement loop in successive cycles. This parameter was approximated as the ratio of the applied load range ΔF_i to the corresponding vertical displacement range $\Delta \delta_i$, in accordance with Equation 1:

$$K_i = \frac{\Delta F_i}{\Delta \delta_i} = \frac{F_{i,\max} - F_{i,\min}}{\delta_{i,\max} - \delta_{i,\min}}, \quad (1)$$

where: $F_{i,\max}$ and $F_{i,\min}$ denote the maximum and minimum force values in the i -th loading cycle, respectively, while $\delta_{i,\max}$ and $\delta_{i,\min}$ are the maximum and minimum vertical displacement values determined as averages of the readings from the linear displacement transducers (LVDTs) located at characteristic points of the system.

The K_i parameter defined in this way describes the global compliance of the tested girder in a given

loading cycle and enables tracking of changes in the response of the entire system rather than merely a single local structural detail. Using the differences ΔF_i and $\Delta \delta_i$ within the same cycle reduces the influence of possible shifts in the displacement reference level, measurement drift, and other additive disturbances, so that the $K_i(N)$ history may be treated as a stable indicator of the degradation trend as a function of cycle count. Moreover, the support and loading arrangement remained unchanged during each test, and no visible signs of progressive support settlement, roller slippage, or fixture adjustment were observed that could plausibly account for the late-stage persistent decrease in K_i . For this reason, the measured stiffness reduction was interpreted primarily as a structural effect rather than as an artefact of boundary-condition evolution. The method used to determine K_i from a single loading cycle is shown schematically in Figure 4. The term “stiffness parameter” is used here deliberately, because the quantity serves not only as a secant-type measure of response within an individual cycle, but also as an operational diagnostic descriptor employed consistently in the interpretative framework developed in this study.

The adopted approach is particularly useful for thin-walled girders with corrugated webs, in which fatigue damage initially develops locally but its consequences may gradually become visible in the global structural response. In this sense, K_i does not replace local observations, but complements them by providing a comparable description of the degradation process in members subjected to different loading histories.

The choice of the stiffness parameter K_i as the primary indicator in the present study follows directly from the objective of the work. The aim is not to replace local fatigue measures such as crack length, local strain accumulation, or detail-based stress assessment, but to identify the moment at which local damage development begins to affect the global structural response of the girder. For this reason, a quantity derived from the global load-displacement loop was considered more appropriate than a local parameter tied to a single measurement point. In the tested full-scale members, local degradation develops in the critical web-to-flange region, whereas K_i provides a comparable description of when the consequences of this local process become measurable at the level of the entire girder. In this sense, K_i should be understood as a global response indicator complementary to, rather than replacing, local fatigue metrics.

Reference level K_0 and the N_{init} damage-initiation criterion

The $K_i(N)$ history alone is not sufficient for unambiguous identification of the moment of damage initiation; therefore, a reference level K_0 corresponding to the initial stage of stable member response was introduced. K_0 was defined as a representative stiffness value within the cycle range for which $K_i(N)$ remained practically constant, i.e., showed no persistent downward trend and reflected the undamaged global response of the tested girder. The parameter K_0 therefore served

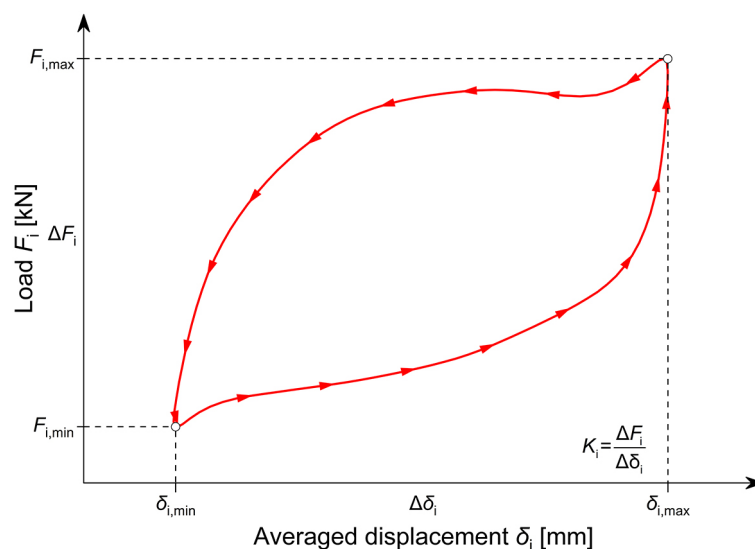


Figure 4. Determination of the global stiffness parameter K_i from a single load-displacement cycle

as the reference point for further assessment of stiffness changes as cyclic loading progressed. The moment of damage initiation was taken as the number of cycles at which a persistent 5% decrease in K_i relative to the reference level K_0 was observed. The corresponding cycle count was denoted N_{init} . The adopted 5% threshold was treated as a compromise between sensitivity to early degradation of structural response and robustness against measurement scatter, local signal fluctuations, and possible displacement-measurement drift. The persistence condition means that N_{init} was not identified from a single incidental drop in K_i , but from the point onwards at which the observed stiffness reduction remained present in the subsequently analysed cycles.

To assess the robustness of the adopted criterion, a simplified sensitivity analysis was performed for additional stiffness-degradation thresholds of 3% and 7% relative to K_0 . The purpose of this analysis was to verify whether the choice of threshold affects only the absolute value of N_{init} or also the overall interpretation of the degradation history. On the basis of the $K_i(N)$ histories for test girders TG2 and TG3, it was found that changing the threshold shifts the position of N_{init} along the cycle-count axis but does not change the qualitative picture of the phenomenon: in both cases, damage initiation remains clearly earlier than the number of cycles to failure N_{fail} , and the degradation history preserves the same character. The 3% threshold is more sensitive to minor fluctuations in $K_i(N)$, whereas the 7% threshold identifies degradation later, i.e., closer to the final stage of rapid stiffness loss. For this reason, the 5% threshold was adopted as an intermediate solution, offering greater robustness against accidental signal disturbances than the 3% threshold while still enabling earlier identification of persistent degradation than the 7% threshold.

The criterion defined in this way is operational and diagnostic in nature. It does not indicate final failure of the member, but rather identifies the stage at which local damage development begins to be reflected in a measurable change in the global structural response. It should therefore not be interpreted as corresponding to a unique local state such as a specific crack length or the formal onset of local buckling. Rather, it denotes the cycle at which accumulated local changes become sufficiently developed to produce a persistent effect in the global response of the girder. In this sense, N_{init} should be interpreted as

an intermediate parameter between the stage of apparently stable system response and the attainment of the number of cycles to failure N_{fail} . This enables not only comparison of the durability of members subjected to different loading programmes, but also distinction between the degradation-initiation stage and the stage leading directly to final failure.

The adopted 5% threshold should be understood as an operational diagnostic criterion rather than a universal physical limit. Its purpose is to identify the stage at which the stiffness history no longer fluctuates around the initial stable level, but begins to exhibit a persistent downward trend that can reasonably be interpreted as a measurable consequence of structural degradation in global terms. In the present study, this threshold was selected as a compromise between excessive sensitivity to incidental signal variations and overly late identification of degradation. The accompanying sensitivity analysis for the 3%, 5%, and 7% thresholds confirms that, although the absolute position of N_{init} changes, the overall interpretation of the degradation history remains unchanged. It should also be emphasized that N_{init} is not interpreted as the instant of first micro-crack formation or of a unique local failure event, but rather as the stage at which the accumulation of local changes becomes sufficiently developed to influence the global response in a persistent and measurable manner. The sensitivity analysis therefore supports the use of the 5% threshold as a robust and practically interpretable intermediate criterion for identifying the onset of persistent degradation in the global structural response. The results of the simplified sensitivity analysis for the 3%, 5%, and 7% thresholds are summarised in Table 2, while the graphical identification of N_{init} for the adopted 5% threshold is presented in Figure 5.

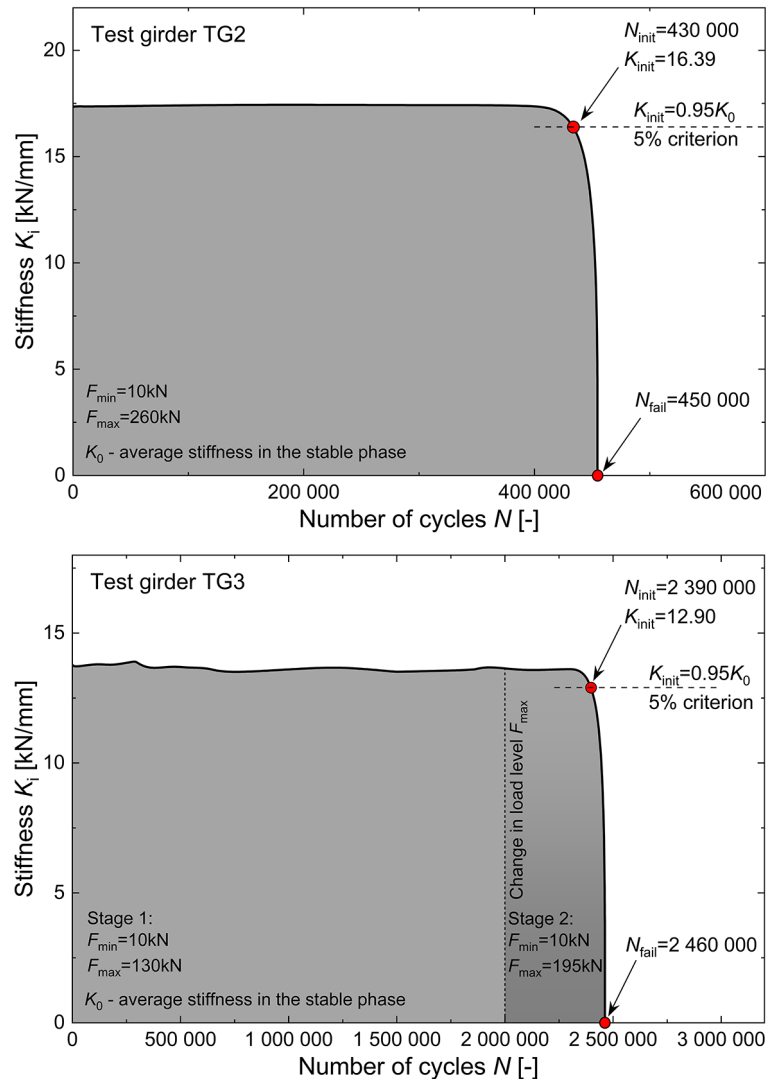
$K_i(N)$ histories and the relationship between N_{init} and N_{fail}

To illustrate the adopted criterion and assess the relationship between the moment of damage initiation and final failure, the $K_i(N)$ histories for test girders TG2 and TG3, subjected to cyclic loading until failure, were analysed (Figure 5). The plots indicate the N_{init} values corresponding to the 5% threshold together with the numbers of cycles to failure N_{fail} .

For test girder TG2, loaded within the range $F_{min} = 10$ kN and $F_{max} = 260$ kN, the $K_i(N)$ history

Table 2. Sensitivity analysis of N_{init} with respect to the adopted global stiffness-degradation threshold

Test girder	K_0	K_{init}			N_{init}			N_{fail}
		3%	5%	7%	3%	5%	7%	
	[kN/mm]	[kN/mm]	[kN/mm]	[kN/mm]	$[\times 10^6]$	$[\times 10^6]$	$[\times 10^6]$	$[\times 10^6]$
TG2	17.25	16.74	16.39	16.05	0.42	0.43	0.44	0.45
TG3	13.58	13.17	12.90	12.63	2.38	2.39	2.41	2.46


Figure 5. Global stiffness K_i as a function of cycle count N : (a) test girder TG2, (b) test girder TG3

remained almost constant for most of the test duration (Figure 5a). A clear and persistent decrease in stiffness was observed only in the final stage of loading, leading to identification of $N_{init} = 430\,000$ cycles. Final failure occurred at $N_{fail} = 450\,000$ cycles, which means that the interval between the onset of persistent global degradation and member failure was short. This history indicates that, at a high load level, degradation of the global response became visible relatively late but then developed very rapidly.

A different response history was obtained for test girder TG3, as shown in Figure 5b. In the first stage of the test, conducted within the range $F_{min} = 10\text{ kN}$ and $F_{max} = 130\text{ kN}$, K_i remained almost constant up to about 2 000 000 cycles. After increasing the load level to $F_{max} = 195\text{ kN}$, the stiffness history still did not show an immediate persistent decrease, which means that the change in loading programme itself did not automatically trigger the damage-initiation criterion. Only in the later part of the test was $N_{init} = 2\,390\,000$

cycles identified, whereas final failure occurred at $N_{\text{fail}} = 2\,460\,000$ cycles. This history confirms that K_i is sufficiently robust to distinguish a change in loading conditions from the actual onset of persistent degradation of structural response.

Comparison of test girders TG2 and TG3 shows that in both cases N_{init} occurs clearly earlier than N_{fail} , although the duration of the phase between the onset of degradation and final failure remains limited (Figure 5). This means that K_i does not identify the failure event itself, but rather an earlier stage at which damage begins to have measurable consequences for the global system response. At the same time, the $K_i(N)$ histories of both girders indicate that most of fatigue life corresponds to a phase of almost stable stiffness, whereas the final degradation is strongly nonlinear and develops over a relatively short cycle interval. For further interpretation, it is also important that the relationship between N_{init} and N_{fail} can be analysed together with local observations of member condition. This makes it possible to verify whether the moment identified globally on the basis of $K_i(N)$ is confirmed by changes in local web response and by the development of fatigue-damage symptoms. In the present study, however, this relationship has an interpretative rather than calibrative character. The available measurements support the physical meaning of N_{init} , but they do not justify a one-to-one conversion of this parameter into a unique local fracture-mechanics or local-stability criterion.

Local damage symptoms as validation of the N_{init} criterion

To assess the physical interpretability of N_{init} determined from the global stiffness history $K_i(N)$, the strain distributions recorded in measuring section A located in the shear zone, close to the later failure region, were analysed. The location of this section corresponds to the fatigue-failure mode observed in both test girders TG2 and TG3 and is shown in Figure 6.

Representative strain distributions recorded for test girder TG2 immediately before and after exceeding N_{init} are presented in Figure 7. This comparison makes it possible to assess local structural response in two states: before the onset of persistent global stiffness degradation and after entry into the stage of developed degradation identified from the criterion based on a decrease in K_i .

Before N_{init} , the strain distributions were characterised by a relatively uniform pattern, without distinctly pronounced local irregularities in the analysed section. This stage corresponded to the response range in which the global stiffness described by K_i remained practically unchanged. Thus, despite the cyclic loading, the girder response still remained close to the undamaged state in global terms.

After N_{init} was exceeded, the strain distributions showed a more disturbed pattern in the critical web region. In particular, the response became

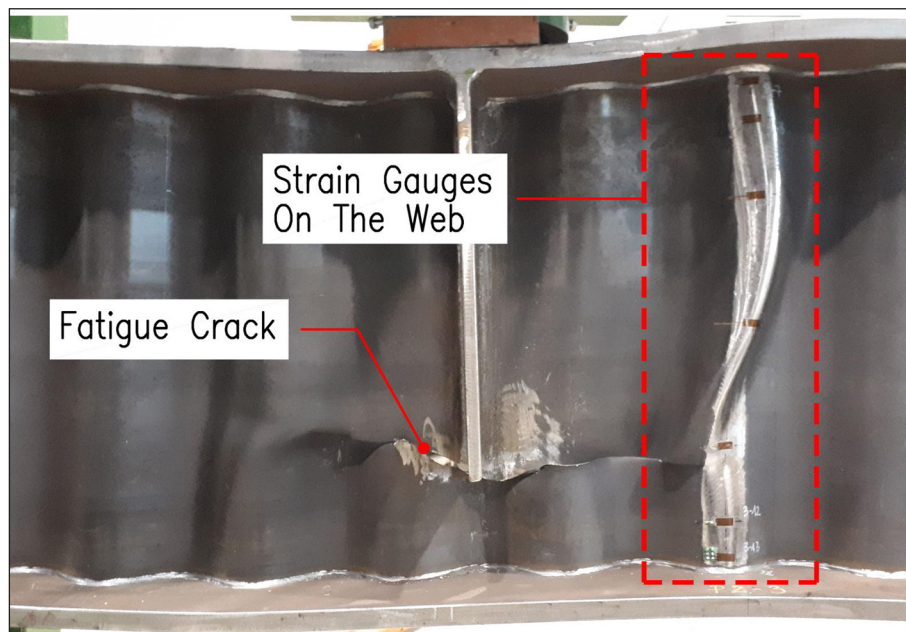


Figure 6. Location of measuring section A in the failure region corresponding to the fatigue-failure mode observed in both test girders TG2 and TG3

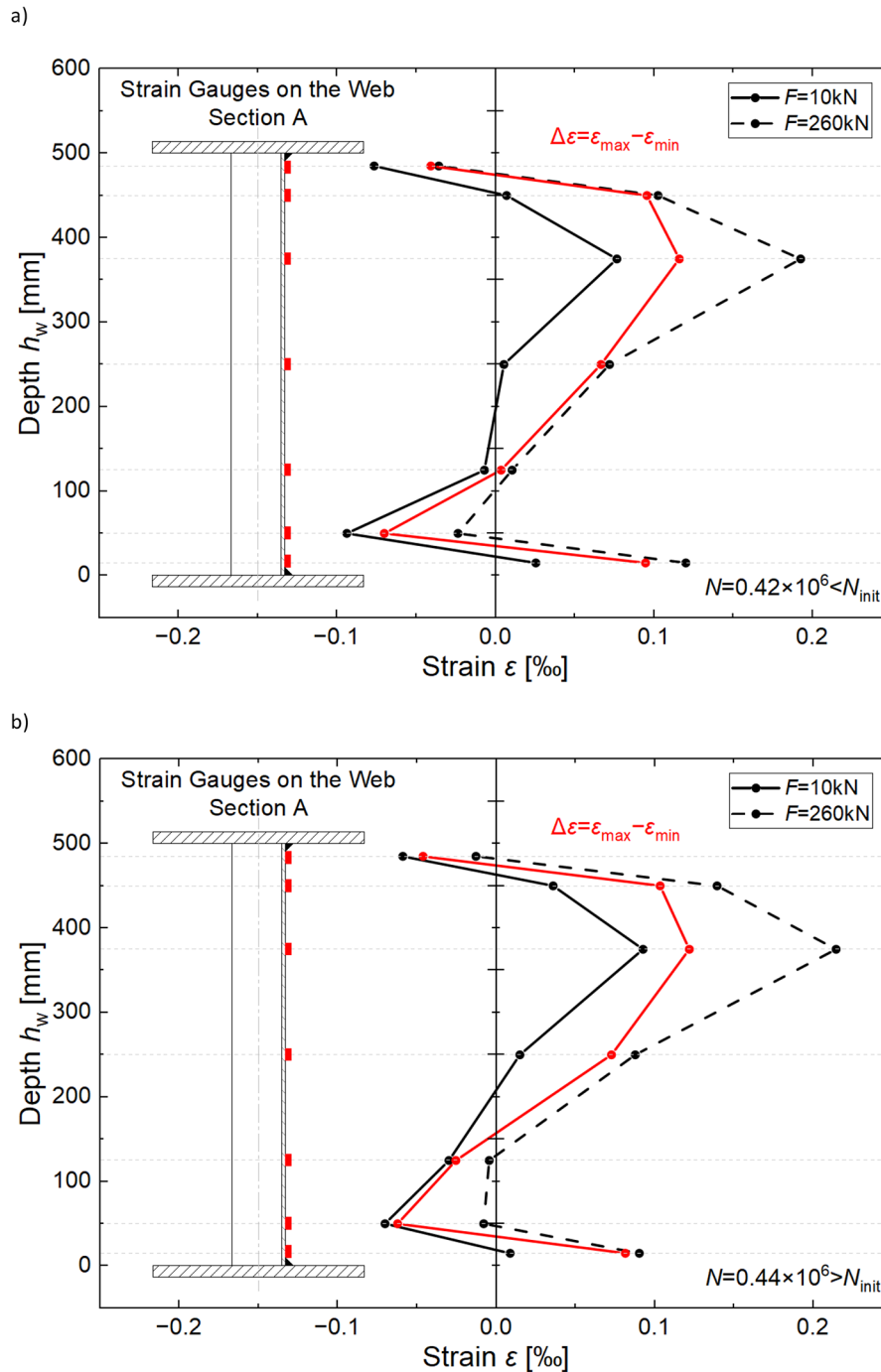


Figure 7. Representative distributions of normal strains ϵ along the web depth during cyclic loading in test girder TG2: (a) stage before exceeding N_{init} ; (b) stage after exceeding N_{init}

less uniform and more locally differentiated in the region where fatigue damage later developed. This suggests that the stage identified globally on the basis of the persistent decrease in K_i is accompanied by a change in local member response rather than merely by an incidental disturbance in the measurement signal.

It should be noted, however, that the degradation process is local in nature and may start

earlier, before its consequences become clearly visible in the global structural response. In this sense, N_{init} does not denote the moment at which the first micro-damage appears, but rather the moment from which the accumulation of local changes finds measurable reflection in the $K_i(N)$ history. K_i therefore does not replace local observations, but allows them to be expressed by means of a comparable global indicator useful for the

analysis of members subjected to different cyclic histories. The comparison of strain distributions recorded before and after exceeding N_{init} should therefore be treated as illustrative support for the interpretation of the global stiffness criterion. The observed changes in the response pattern suggest that the stage identified by the persistent decrease in K_i is accompanied by a more disturbed local response in the critical web region. In this sense, Figure 7 supports the physical interpretation of N_{init} , although it is not intended to constitute an independent quantitative proof of local damage evolution by itself.

Once interpreted in this way, N_{init} can be used not only to describe degradation in cyclic tests to failure, but also to support interpretation of the consequences of prior loading for residual load-carrying capacity and the final failure mechanism of members tested after preliminary fatigue loading.

Normalized two-stage representation of stiffness degradation

To complement the diagnostic interpretation based on the parameters K_i , K_0 , and N_{init} , the experimentally observed stiffness histories were additionally expressed in a normalized two-stage form. The purpose of this representation is not to formulate a general design relationship, but to provide a compact comparative and interpretative representation of the global stiffness-degradation trajectory observed in the analysed girders.

A normalized stiffness parameter was introduced as:

$$\eta_k(N) = \frac{K_i(N)}{K_0} \quad (2)$$

where: $K_i(N)$ is the stiffness parameter determined for the i -th cycle and K_0 is the reference stiffness corresponding to the initial stage of stable response.

To enable comparison of girders with different fatigue lives, the number of cycles was expressed in normalized form as:

$$n = \frac{N}{N_{fail}} \quad (3)$$

where: N is the current number of cycles and N_{fail} is the number of cycles to failure. In addition, the normalized damage-initiation point was defined as:

$$n_{init} = \frac{N_{init}}{N_{fail}} \quad (4)$$

On this basis, the stiffness-degradation history may be represented by the following two-stage relationship:

$$n_k(n) = \begin{cases} 1 - 0.05 \left(\frac{n}{n_{init}} \right), & n \leq n_{init} \\ 0.95 - (0.95 - \eta_{k,f}) \left(\frac{n - n_{init}}{1 - n_{init}} \right)^m, & n_{init} < n \leq 1 \end{cases} \quad (5)$$

where: $\eta_{k,f} = K_f/K_0$ is the normalized stiffness at the end of the normalized history, K_f is the corresponding stiffness value, and m is a shape parameter controlling the rate of stiffness degradation in the final stage of fatigue life.

The proposed form reflects the two characteristic phases observed in the histories of test girders TG2 and TG3. In the first phase, corresponding to $n \leq n_{init}$, the normalized stiffness remains close to unity and exhibits only a slight downward trend. This stage represents the response range in which local damage may already accumulate, but its consequences are not yet sufficiently developed to produce a persistent global stiffness reduction exceeding the adopted criterion. In the second phase, beginning at n_{init} , the stiffness decreases in a persistent and strongly nonlinear manner, which corresponds to the stage in which local degradation becomes sufficiently developed to produce measurable consequences for the global structural response.

The physical interpretation of the parameters in Equation 5 is straightforward. The parameter n_{init} defines the transition from the stage of apparently stable response to the stage of developed degradation. The parameter $\eta_{k,f}$ describes the normalized stiffness level at the end of the normalized history. The exponent m controls the curvature of the degradation trajectory and therefore reflects how rapidly the stiffness decreases once the onset of persistent degradation has been exceeded. Higher values of m correspond to a more abrupt stiffness loss concentrated near failure, whereas lower values indicate a more gradual degradation development after N_{init} .

The adopted representation is continuous at the transition point $n = n_{init}$, where the normalized

stiffness reaches the level $\eta_K = 0.95$, consistent with the definition of N_{init} based on a persistent 5% decrease in K_i relative to K_0 . In this way, the normalized representation remains directly linked to the previously introduced diagnostic criterion and preserves the physical meaning of the transition between the two response stages.

The normalized stiffness histories of test girders TG2 and TG3, together with the corresponding representations obtained using Equation 5, are shown in Figure 8. The proposed model captures

the main features of the normalized degradation histories, including the transition at n_{init} and the final stage of accelerated stiffness loss preceding failure. The basic normalized parameters of the degradation history are summarised in Table 3, whereas the fitted parameters of Equation 5 are listed in Table 4. In the fitted representation, the value $\eta_{K,f} = 0$ was adopted as the normalized terminal level corresponding to the end of the degradation history at failure, so that the parameter m controls the curvature of the descending branch

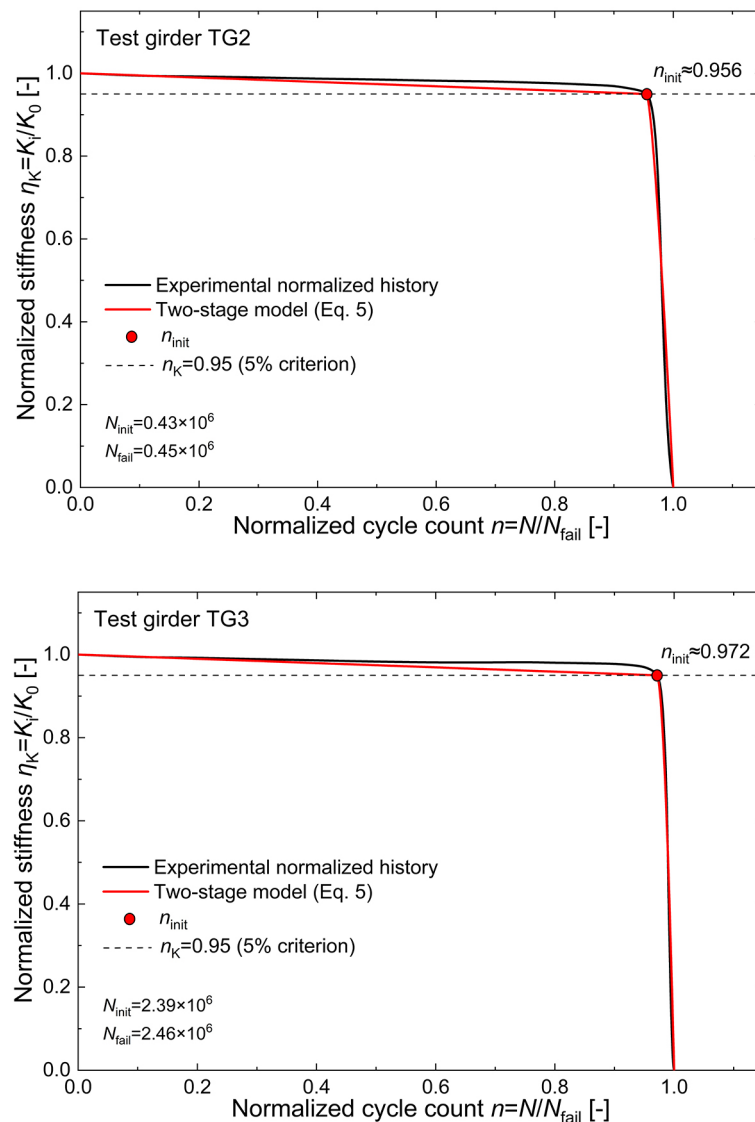


Figure 8. Normalized stiffness histories and fitted two-stage model: (a) TG2; (b) TG3

Table 3. Basic normalized parameters of the degradation history

Test girder	K_0	N_{init}	N_{fail}	n_{init}	$\eta_{K,init}$
	[kN/mm]	[10^6]	[10^6]	[-]	[-]
TG2	17.25	0.43	0.45	0.956	0.95
TG3	13.58	2.39	2.46	0.972	0.95

leading to the experimentally observed final state. The goodness of fit of Equation 5 was assessed by the root-mean-square error (RMSE), calculated for the normalized stiffness variable η_K as:

$$\text{RMSE} = \sqrt{\frac{1}{p} \sum_{j=1}^p (\eta_{K,j}^{\text{exp}} - \eta_{K,j}^{\text{mod}})^2} \quad (6)$$

where: p is the number of compared points, $\eta_{K,j}^{\text{exp}}$ is the normalized stiffness value taken from the normalized history, and $\eta_{K,j}^{\text{mod}}$ is the corresponding value obtained from Equation 5.

Synthesis of the significance of K_i and N_{init}

The analysis shows that K_i can serve as a useful global indicator of response degradation in girders with sinusoidally corrugated webs subjected to cyclic loading. In contrast to the classical description of fatigue life based solely on the number of cycles to failure N_{fail} , the $K_i(N)$ history makes it possible to identify an earlier stage of degradation at which local damage begins to produce measurable consequences for the global structural response.

The introduction of the reference level K_0 and the operational criterion N_{init} , based on a persistent 5% decrease in stiffness, makes it possible to distinguish two important phases of member response: the stage of apparently stable response and the stage of developed degradation preceding final failure. Comparison of N_{init} and N_{fail} for test girders TG2 and TG3 shows that most of fatigue life corresponds to a phase of almost unchanged stiffness, whereas the final degradation develops over a relatively short cycle interval.

At the same time, comparison of $K_i(N)$ histories with local strain distributions supports the interpretation that the N_{init} criterion has physical meaning and is not merely a formal mathematical indicator. K_i does not replace local observations, but expresses them in terms of a comparable global indicator useful for analysing members subjected to different loading histories.

Table 4. Parameters of the normalized two-stage model defined by Equation 5

Test girder	$\eta_{K,i}$	m	RMSE
	[-]	[-]	[-]
TG2	0.000	1.375	0.0553
TG3	0.000	1.738	0.0407

The parameters K_i and N_{init} defined in this way provide a basis for further interpretation of the effects of prior cyclic loading and the subsequent ultimate response, including residual load-carrying capacity and a possible change in the failure mechanism of members tested after preliminary fatigue loading.

The proposed framework therefore operates at two complementary levels. At the diagnostic level, the parameters K_i , K_0 , and N_{init} make it possible to identify the onset of persistent degradation in the global structural response and to relate it to local damage symptoms. At the comparative-interpretative level, the normalized two-stage representation provides a compact representation of the degradation trajectory up to failure. Taken together, these elements provide a more complete basis for analysing the effects of cyclic-loading history and for interpreting the subsequent ultimate response of girders with sinusoidally corrugated webs.

RESIDUAL LOAD-CARRYING CAPACITY AND FAILURE MECHANISM AFTER PRIOR CYCLIC LOADING

Scope of the residual load-capacity analysis

The residual load-carrying capacity test procedure comprised preliminary cyclic loading of test girders TG4 and TG5 according to the adopted loading programmes, followed by static tests with monotonically increasing load until failure. The transition between the cyclic-loading stage and the static test was carried out without changing the test configuration. During the static tests, the load-displacement response was recorded and the development of strains and damage in the critical structural zones was monitored. The recorded data were used to determine the ultimate load-carrying capacities of test girders TG4 and TG5 after a history of cyclic loading and to compare their response directly with that of the reference girder TG1.

In the analysis of test girders TG4 and TG5, particular attention was paid to whether the degradation previously identified on the basis of K_i and N_{init} could serve as a useful reference for interpreting the final response in the static test. The key issue therefore concerned not only the value of residual load-carrying capacity after prior cyclic loading, but above all the consequences that the

previously identified global degradation may have for the ultimate response and the governing failure mechanism. Within this framework, the results for TG4 and TG5 serve as a check of the effects of degradation identified earlier on the basis of the $K_i(N)$ history and the N_{init} moment.

For this reason, the load-displacement curves and the corresponding ultimate capacities of test girders TG4 and TG5 were first compared with the result obtained for the reference girder TG1. The final failure mechanisms of both girders were then analysed, with attention paid to whether a similar level of capacity reduction might lead to different ultimate states. Such a comparison

allows assessment of whether information on the residual load-carrying capacity alone is sufficient to describe the effects of prior loading, or whether it is necessary to additionally consider the preceding degradation history characterised by $K_i(N)$, the $N_{init}-N_{fail}$ relationship, and local damage symptoms.

Reduction in ultimate load capacity after cyclic-loading history

Table 5 summarises the ultimate load-carrying capacities of test girders TG4 and TG5 after prior cyclic loading and relates them to

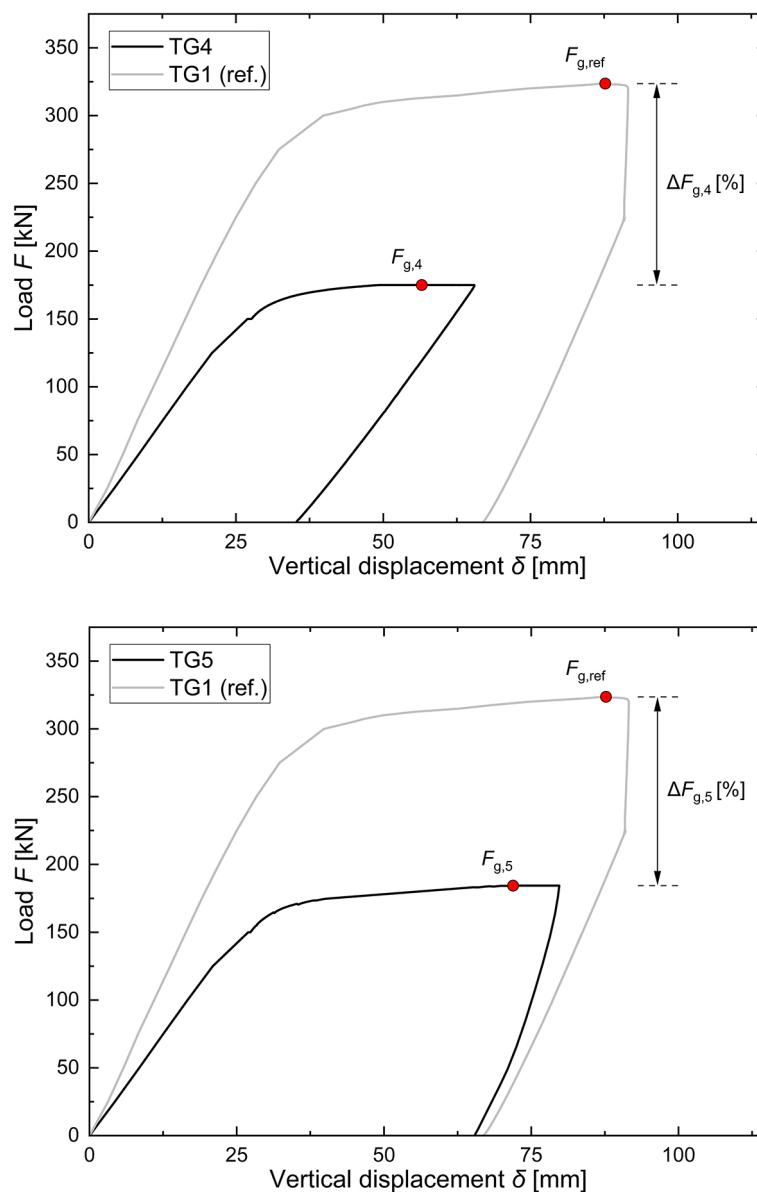
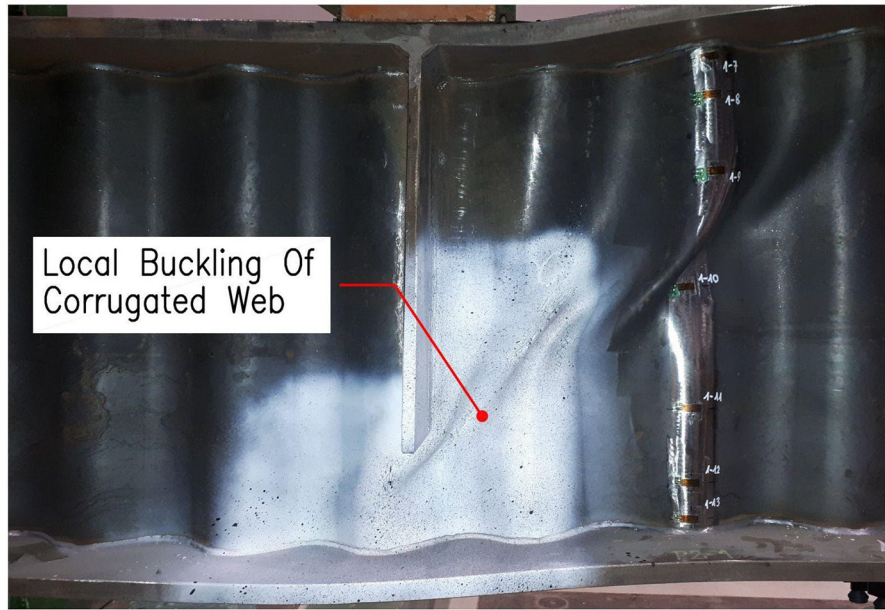


Figure 9. Comparison of the load-displacement (F - δ) curves of the girders after preliminary fatigue loading with the curve of the reference girder TG1: (a) test girder TG4, (b) test girder TG5. The ultimate capacities $F_{g,i}$ and the capacity reductions $\Delta F_{g,i}$ relative to $F_{g,ref}$ are indicated

a)



b)

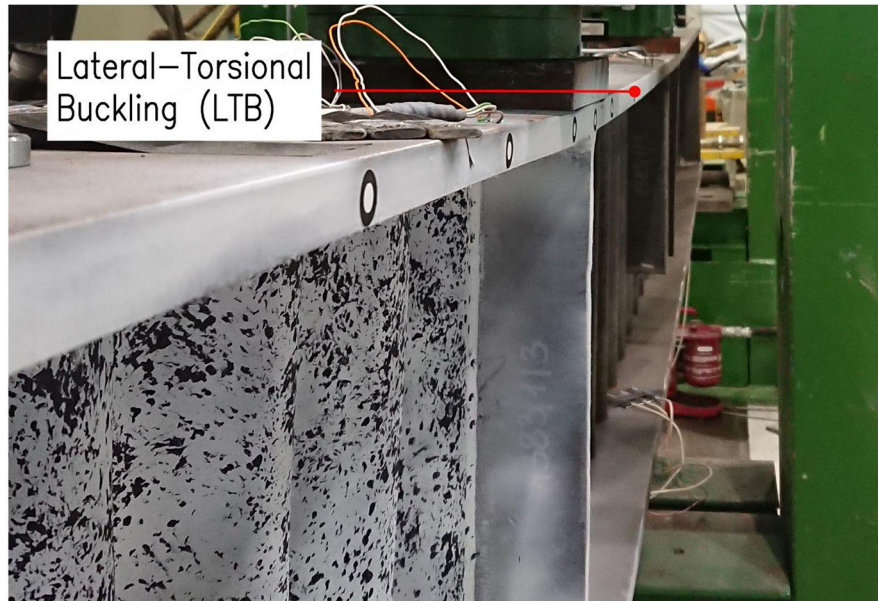


Figure 10. Failure modes of the test girders after preliminary cyclic loading and static testing: (a) TG4 - local failure in the loading zone; (b) TG5 - activation of the global lateral-torsional buckling (LTB) mechanism after prior degradation

the result obtained for the reference girder TG1. The reduction in ultimate load-carrying capacity ΔF_g was defined as the percentage loss of capacity of the tested girder after cyclic loading relative to the reference girder TG1, in accordance with Equation 7:

$$\Delta F_g = \frac{F_{g,ref} - F_{g,i}}{F_{g,ref}} \cdot 100\% \quad (7)$$

where: $F_{g,ref}$ is the ultimate load-carrying capacity of the reference girder TG1, and $F_{g,i}$ is the ultimate load-carrying capacity of the girder after cyclic-loading history. For the reference girder, $\Delta F_g = 0\%$ was adopted.

In both cases, a significant reduction in ultimate load-carrying capacity was found relative to the reference girder, with a similar level of

reduction. The load-displacement curves confirm that the degradation developed during the cyclic-loading stage had significant consequences for the subsequent static response (Figure 9). In this sense, the ultimate load-carrying capacity after cyclic loading should be interpreted as the final effect of previously developing degradation, rather than as an independent parameter describing only the last stage of the test.

Failure mechanism of test girders TG4 and TG5

Analysis of the final failure modes of test girders TG4 and TG5 complements the assessment of the consequences of degradation previously identified on the basis of K_i and N_{init} , making it possible to determine how developed degradation is reflected in the ultimate response of the member. Examples of the failure modes observed after the static tests are presented in Figure 10.

For test girder TG4, failure occurred in a manner analogous to that of the reference girder TG1, i.e., as a result of local web instability in the region of transverse-force application (Figure 10a). The static test and the observed failure mode did not indicate the occurrence of global structural instability. This means that the previously developed degradation, despite the significant reduction in ultimate load-carrying capacity, did not in this case lead to a change in the governing ultimate state, but manifested itself primarily as a reduction in local resistance within the critical zone.

A quantitatively important observation is that this local-type response in TG4 was accompanied by a substantial reduction in ultimate load-carrying capacity relative to the reference girder. Thus, prior cyclic loading did not merely accelerate the attainment of the same ultimate state, but led to a measurable weakening of the member while preserving the local character of the governing failure mechanism. In this sense, TG4 represents a case in which degradation developed to a structurally significant level without causing a transition to a different ultimate mode.

A different response was observed for test girder TG5, as shown in Figure 10b. Final failure was governed by global lateral-torsional buckling (LTB), which became apparent after prior cyclic loading. The observed failure mechanism differed from the reference mechanism despite the identical geometry, material, and static arrangement of the tested girders, indicating that the

consequences of previously developed degradation may also be manifested at the level of global response and system stability.

In practical terms, the contrast between TG4 and TG5 is particularly important because the reduction in ultimate load-carrying capacity was of similar magnitude in both cases, whereas the final structural response was not. For TG4, the previously developed degradation remained associated with a local mechanism analogous to that observed in the reference girder. For TG5, however, the degradation history was accompanied by activation of a global lateral-torsional buckling mechanism. This shows that comparable values of residual strength reduction do not necessarily correspond to the same structural condition at failure and that the degradation history must be interpreted together with the governing failure mode.

The practical significance of this observation lies in the fact that prior cyclic loading did not merely reduce the load-carrying capacity by a comparable percentage in both girders, but was also associated with different ultimate states. In TG4, the degradation was reflected mainly in weakening of local resistance in the critical zone, whereas in TG5 the final response involved activation of a global lateral-torsional buckling mechanism. This distinction supports the conclusion that the degradation history identified earlier by means of K_i and N_{init} is relevant not only to residual strength reduction, but also to interpretation of how the governing failure mode may change after prior cyclic loading.

The results therefore indicate that the final failure modes should be interpreted as consequences of the previously developing degradation of global response described by the $K_i(N)$ history and the N_{init} moment. In this sense, the results for TG4 and TG5 do not serve merely as isolated residual-strength values, but as evidence that prior cyclic loading may be associated not only with a reduction in ultimate load-carrying capacity, but also with a different governing ultimate mechanism. The comparison further shows that the same order of capacity loss may correspond to fundamentally different final structural states.

Significance of the description based on K_i and N_{init} for the interpretation of residual load-carrying capacity

The results obtained for test girders TG4 and TG5 show that a similar reduction in ultimate

load-carrying capacity may coexist with a different final member response; therefore, the parameter F_g should be interpreted together with the earlier degradation history described by $K_i(N)$ and N_{init} .

In the present test series, this conclusion is supported by the fact that both pre-fatigued girders exhibited a marked reduction in ultimate load-carrying capacity relative to the reference member, yet the associated ultimate responses were different. One girder failed by a local mechanism analogous to that of the reference specimen, whereas the other exhibited global lateral-torsional buckling after prior cyclic degradation. This combination of similar quantitative capacity loss and different qualitative failure response provides the main justification for treating residual load-carrying capacity and degradation history as complementary rather than interchangeable descriptors.

Within this framework, K_i and N_{init} provide a useful reference for interpreting the effects of prior loading. The $K_i(N)$ history makes it possible to track the gradual degradation of global response, whereas N_{init} separates the phase of apparently stable response from the stage at which damage begins to produce measurable consequences for global system stiffness. Residual load-carrying capacity should therefore not be interpreted as an isolated result of the final static test, but as an effect of the earlier degradation history developing during cyclic loading.

From the standpoint of structural assessment, this means that the residual load-carrying capacity should not be interpreted as a single standalone indicator of the consequences of cyclic loading. A member that has lost a similar percentage of its load-carrying capacity may still differ substantially in terms of the way degradation is distributed and in terms of its susceptibility to a local or global ultimate mechanism. For this reason, information on the degradation trajectory expressed by $K_i(N)$, together with the position of N_{init} , may provide important supplementary context for judging whether prior cyclic loading has primarily weakened a local critical zone or has also affected the broader stability conditions of the member.

From an interpretative standpoint, it is therefore important to consider jointly the $K_i(N)$ history, the N_{init} moment, the value of ultimate load-carrying capacity, and the final failure mode. Only such a combination makes it possible to distinguish cases in which earlier degradation mainly leads to local weakening from those in which it also affects global system compliance and activation

of a different ultimate state. In this sense, K_i and N_{init} are not used for direct prediction of F_g , but for an ordered interpretation of the processes leading to loss of load-carrying capacity after prior cyclic loading. The present results therefore support the view that assessment of members subjected to repeated loading should account not only for the amount of residual strength loss, but also for the form in which the earlier degradation becomes manifested in the final structural response.

DISCUSSION

Significance of K_i as a global degradation indicator

The analysis indicates that K_i may be treated as a useful global indicator of response degradation in girders with sinusoidally corrugated webs subjected to cyclic loading. In contrast to the classical description of fatigue life based solely on the number of cycles to failure N_{fail} , the $K_i(N)$ history makes it possible to identify an earlier stage of degradation at which damage development begins to affect the response of the entire system. In this sense, K_i is not used to describe the failure event itself, but to capture the transition from the state of apparently stable response to the state of developed structural degradation.

The significance of such an approach is particularly evident for thin-walled members, in which damage is initially local and may for a long time not cause distinct changes in the final load-carrying capacity. In girders with corrugated webs, local fatigue damage develops in regions of stress concentration and is related to the response of critical welded details, whereas K_i makes it possible to assess when accumulation of these changes begins to affect structural response in global terms. This links local observations with the behaviour of the entire girder without reducing the interpretation to a single measurement point or one structural detail.

This approach is consistent with the general trend reported in the literature on corrugated-web girders, according to which the response of such members under cyclic loading results from interaction between local and global effects [6,15]. Available studies have most often focused either on the strength and overall behaviour of corrugated-web girders or on local fatigue aspects of critical welded details, including detail categories and

stress-concentration factors [10,19]. Against this background, K_i may be regarded as an attempt to organise these two levels of description by introducing a global degradation indicator that remains linked to local damage development but is not limited to the analysis of a single detail. It should also be noted that the literature on corrugated-web girders is still dominated either by strength-and-stability descriptions or by local fatigue analyses of critical details, whereas a simple operational indicator linking local damage development with degradation of the global response of the entire member is still lacking.

Another advantage of K_i is that it is determined from the global load-displacement response and therefore has a comparative character that allows its use for members subjected to different cyclic programmes. This obviously does not mean that K_i replaces local damage observations. On the contrary, its usefulness lies precisely in organising local phenomena at the global level and in allowing assessment of when damage development ceases to be only a local phenomenon and begins to affect performance of the entire load-bearing system. From this viewpoint, K_i may be treated as an intermediate indicator between the local condition of the material/detail and the global ability of the structure to continue operating under cyclic loading.

Relationship between N_{init} , N_{fail} and local damage symptoms

The introduction of the reference level K_0 and the operational criterion N_{init} , based on a persistent 5% decrease in K_i , made it possible to separate quantitatively the moment of initiation of global degradation from the instant of final failure. For both members subjected to cyclic loading until failure, N_{init} occurred earlier than N_{fail} , which means that final failure was preceded by a stage of measurable, but not yet critical, degradation of global response. The number of cycles to failure alone therefore does not provide a complete description of the degradation process, because it does not distinguish the phase of stable response from the phase of final weakening leading to failure.

From a physical standpoint, however, it should be emphasised that N_{init} does not denote the moment at which the first micro-damage appears. In steel structures subjected to cyclic loading, initiation of local degradation may begin

earlier, before its effects become visible in the global response. N_{init} should therefore be interpreted as the moment from which accumulation of local changes reaches a level sufficient to cause a persistent and measurable decrease in global stiffness. Such an interpretation is consistent both with the $K_i(N)$ history and with the observed changes in local strain distributions before and after exceeding N_{init} .

Interpretation of the relationship between N_{init} and N_{fail} is consistent with the classical view of high-cycle fatigue in steel members, in which a distinction is made between the stage of damage initiation and the stage of propagation leading to final failure [11,32]. In design practice, fatigue life is usually described by $S-N$ relationships, which works well at the level of detail assessment but does not directly indicate when damage development begins to affect the response of the whole system [11]. In this sense, N_{init} does not compete with the classical durability description, but complements it by introducing an intermediate stage associated with the onset of persistent degradation in global terms. The N_{init} criterion proposed here is therefore not an alternative to classical detail-based fatigue-life assessment according to the $S-N$ approach, but a complement to it at the level of global structural response, which may be of considerable interpretative value for corrugated-web girders.

The significance of this relationship is also confirmed by the sensitivity analysis of the adopted degradation threshold. Considering the levels of 3%, 5%, and 7% relative to K_0 changes the absolute value of N_{init} , but does not alter the general interpretation of the degradation history: in every case N_{init} remains earlier than N_{fail} , and the $K_i(N)$ history retains the same character. This means that the 5% threshold should not be treated as a single universal value, but as a rational operational compromise between too-early identification of degradation and too-late capture of a persistent downward trend. In the analysed series, this choice proved sufficiently robust against fluctuations in the history and at the same time sufficiently sensitive to distinguish the stage of stable response from the stage of developed degradation.

Residual load-carrying capacity and failure mechanism in the light of prior degradation

In the present study, the key result is not the value of ultimate load-carrying capacity itself

after prior cyclic loading, but the possibility of globally identifying the onset of persistent degradation on the basis of K_i and N_{init} ; the results for TG4 and TG5 serve primarily to show what consequences such identified degradation may have for the ultimate response of the member.

The results obtained for test girders TG4 and TG5 show that ultimate load-carrying capacity alone after prior cyclic loading is not sufficient for a complete description of the effects of loading history. In both cases, a significant and similar reduction in ultimate load-carrying capacity was recorded relative to the reference girder TG1, yet the final failure mechanisms were different. This means that a similar level of capacity loss does not necessarily correspond to the same degradation state in terms of response and system stability. The number describing the drop in F_g alone does not indicate how earlier damage affected the final structural response.

In this sense, the effects of prior cyclic loading may be interpreted as a sequence of degradation stages: from the phase of stable response ($K_i \approx K_0$), through the onset of persistent degradation identified as N_{init} , to the stage of developed degradation, the consequences of which manifest themselves in the ultimate response of the member and, in some cases, also in the final failure mechanism.

For test girder TG4, prior cyclic loading led to a clear weakening of the member but did not change the governing failure mechanism. Final loss of capacity occurred locally, in a manner analogous to that observed in the reference girder. This means that the effects of degradation manifested themselves primarily as a reduction in local resistance in the critical zone, without transition to a global mechanism. Such a case may be interpreted as a situation in which earlier damage develops mainly within the local response of the web and connection details, while its influence on overall system compliance does not reach a level sufficient to trigger a change in the ultimate state.

For test girder TG5, prior degradation also resulted in a significant reduction in load-carrying capacity, but its consequence was a change in the governing failure mechanism and manifestation of global lateral-torsional buckling. This result is particularly important because it shows that prior cyclic loading may affect not only the level of residual load-carrying capacity, but also the manner in which the final ultimate state is activated. The effects of loading history should therefore be

considered not only in terms of ‘how much capacity was lost’, but also in terms of how the response conditions of the system and its susceptibility to a given loss-of-capacity mechanism changed.

The observed influence of loading history on the final response of the members is consistent with tendencies reported in the literature, according to which load range and the associated stress levels play a key role in damage initiation and accumulation of degradation in corrugated-web girders [6,11,32]. The possibility of activating a global mechanism is, in turn, consistent with earlier observations on the susceptibility of corrugated-web girders to interaction between local phenomena and spatial effects [6,14]. Against this background, the results for TG4 and TG5 extend current knowledge by showing that a similar level of capacity reduction may lead to different ultimate states when the earlier degradation develops in different ways.

Comparison of TG4 and TG5 therefore leads to an important interpretative conclusion: a similar reduction in load-carrying capacity may correspond to different mechanical consequences of prior degradation. In one case, degradation mainly leads to weakening of local resistance; in the other, it also affects global system compliance and activation of a different failure mechanism. It is at this point that the value of the description based on K_i and N_{init} becomes most evident. These parameters are not used here to determine F_g directly, but to provide an ordered interpretation of the processes leading to the later loss of load-carrying capacity. Thanks to them, residual load-carrying capacity ceases to be treated as an isolated result of the final static test and becomes the final effect of previously developing degradation.

From a safety-assessment standpoint, this means that comparison of the F_g or ΔF_g values alone is not sufficient for a full evaluation of the effects of prior cyclic loading. A more representative picture is obtained only when ultimate load-carrying capacity is analysed together with the $K_i(N)$ history, the N_{init} moment, local degradation symptoms, and the final failure mode. Such an approach makes it possible to distinguish situations in which prior loading mainly leads to local weakening from those in which it also affects global stability conditions. In this sense, the proposed methodology has not only diagnostic but also interpretative value. From a practical point of view, monitoring stiffness changes may provide

a useful diagnostic tool for assessing members under repeated loading, especially when local damage is not yet readily identifiable visually but is already beginning to affect global response. For corrugated-web girders, such information may be important in assessing whether prior loading history leads only to weakening of local resistance or also increases the risk of activating a different loss-of-capacity mechanism.

Method limitations and directions for further research

The proposed approach has several important limitations. First, the analysis is based on a limited number of test members, which does not yet allow generalised design relationships to be formulated or transition rules between local and global mechanisms to be quantified. Second, the adopted 5% threshold is operational and diagnostic in nature; although the sensitivity analysis confirms its rationality for the analysed series, it should not be treated as a universal value applicable to all girder types and loading histories. Third, no direct measurements of welding residual stresses or out-of-plane geometric imperfections were performed; therefore, their influence

should be treated as included in the response of the ‘as-fabricated’ members rather than as a separately quantified analytical factor.

It should also be emphasized that the present study is not intended to provide a direct code-based design procedure for pre-damaged corrugated-web girders. Current steel design standards, including fatigue-oriented and stability-oriented provisions, provide rules for the design and assessment of structural members and welded details, but they do not directly address the kind of experimentally identified degradation history considered here. For this reason, the proposed framework should presently be understood as complementary to existing design provisions rather than as an alternative to them.

From a practical point of view, the results suggest that monitoring changes in global stiffness may provide useful supplementary information in the assessment of girders subjected to repeated loading, particularly when full local diagnostics of all critical details is not feasible. In such an application, the $K_i(N)$ history and the N_{init} moment would not be used as a direct predictor of remaining strength or remaining fatigue life, but rather as indicators supporting interpretation of the current degradation state of

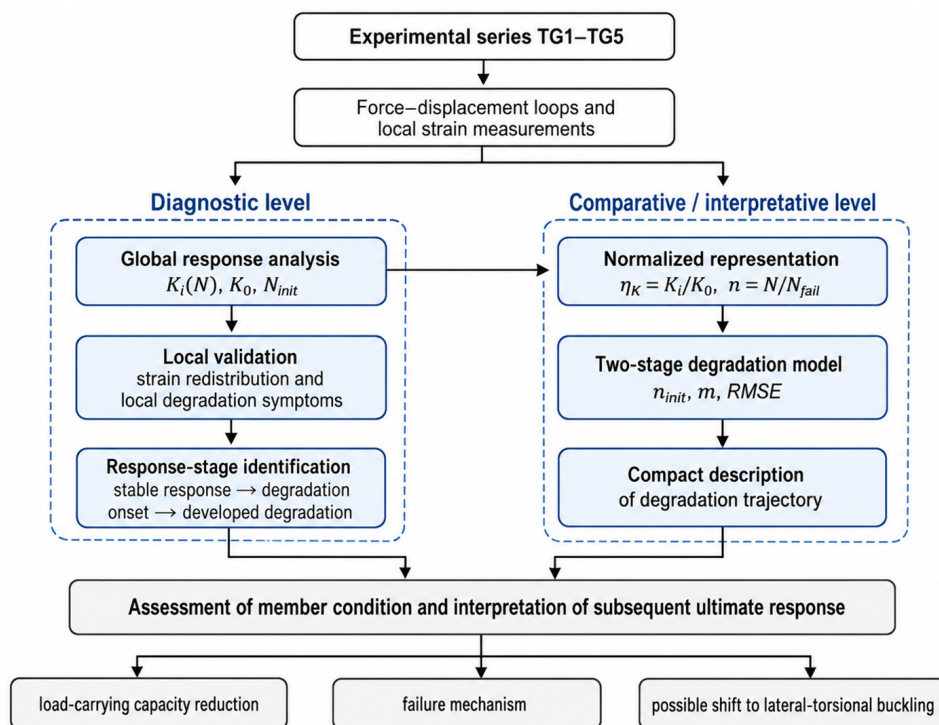


Figure 11. Diagnostic, comparative, and interpretative scheme for assessing the effects of prior cyclic loading in girders with sinusoidally corrugated webs, based on K_i , K_0 , N_{init} , and the normalized two-stage representation of stiffness degradation

the member. Before such an approach could be implemented as a formal inspection or maintenance procedure, however, broader calibration would be required on a larger database covering different load levels, geometries, restraint conditions, and stiffener configurations.

The present study is focused specifically on a stiffness-based indicator derived from the global load-displacement response. A formal benchmark against multiple alternative global-response measures was beyond the scope of the available experimental programme. Nevertheless, the results indicate that K_i provides a practical way of linking local fatigue development with measurable changes in the response of the whole girder. A broader comparative validation against other global indicators should be treated as an important direction for further research.

These limitations are consistent with the general situation described in the literature, in which relatively few full-scale experimental studies have combined long-term cyclic loading with subsequent assessment of residual load-carrying capacity in corrugated-web girders [6,14]. Further studies should therefore include a larger number of members, different utilisation levels, different restraint conditions, and different geometric and technological solutions for thin-walled girders. It would be particularly important to verify to what extent the parameters K_i , N_{init} , and the normalized two-stage representation can be linked not only to degradation diagnostics but also to broader quantitative assessment of structural condition, residual load-carrying capacity, and the probability of a change in the governing failure mechanism. In its present form, the proposed approach should therefore be regarded as a diagnostic, comparative, and interpretative framework for analysing cyclic degradation in girders with sinusoidally corrugated webs. Its value lies in linking the global stiffness history, the moment of persistent degradation initiation, the residual load-carrying capacity, and the final failure mechanism within one consistent description of structural response. At the same time, the current formulation does not yet constitute a general design or life-prediction procedure, and its extension in that direction requires further calibration on a broader experimental and numerical basis.

To summarise the proposed approach, Figure 11 presents a diagnostic, comparative, and interpretative scheme for assessing the effects of prior cyclic loading. The scheme combines analysis

of global response based on K_i , K_0 , and N_{init} with observations of local degradation symptoms and with assessment of ultimate load-carrying capacity and the final failure mechanism.

CONCLUSIONS

The analysis showed that the response of girders with sinusoidally corrugated webs subjected to cyclic loading can be interpreted effectively not only on the basis of the number of cycles to failure, but also by means of global parameters describing the degradation history of the structure. Use of the stiffness parameter K_i and the N_{init} criterion made it possible to link local damage symptoms with the global response of the member and then to relate this degradation to residual load-carrying capacity and the final failure mechanism. On this basis, the following conclusions are drawn:

The stiffness parameter K_i , determined from the global load-displacement response, may be treated as a useful indicator of degradation in girders with sinusoidally corrugated webs subjected to cyclic loading. Its history as a function of cycle count makes it possible to distinguish the stage of apparently stable member response from the stage of developed degradation preceding final failure.

The introduction of the reference level K_0 and the operational criterion N_{init} , based on a persistent 5% decrease in K_i relative to K_0 , enables repeatable identification of damage initiation in terms of the global structural response. In the analysed series, N_{init} occurred earlier than N_{fail} , which confirms the existence of an intermediate stage between stable response and final failure.

Analysis of local strain distributions before and after exceeding N_{init} supports the physical interpretation of this criterion and indicates that it corresponds to a change in local response pattern, although it should not be treated as an independent quantitative measure of local damage evolution.

The observed stiffness histories may be expressed in a normalized two-stage form using the parameters $\eta_K = K_i/K_0$ and $n = N/N_{fail}$. The proposed representation captures the main features of the degradation process, including the transition at n_{init} and the final stage of accelerated stiffness loss preceding failure. In this sense, the approach extends the description of degradation from a purely diagnostic level towards a compact comparative and interpretative representation. For the members tested after prior cyclic loading, it was

found that the degradation identified globally on the basis of K_i and N_{init} has consequences for the subsequent ultimate response of the member. In both cases, a significant reduction in load-carrying capacity relative to the reference girder was recorded, whereas the final failure mechanisms were different. This means that the results for TG4 and TG5 should be treated primarily as a check of the effects of previously identified degradation, rather than as an independent model for assessing residual load-carrying capacity.

Joint analysis of the $K_i(N)$ history, the N_{init} moment, local degradation symptoms, ultimate load-carrying capacity, and failure mode provides a more complete picture of the effects of loading history than an assessment based solely on the number of cycles to failure or on residual load-carrying capacity alone. In this sense, K_i and N_{init} are primarily of diagnostic and interpretative value, while the normalized two-stage representation provides an additional compact representation of the degradation trajectory.

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