Wind field variability in complex terrain: Lessons from the Hardanger Bridge

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Abstract Along the Coastal Highway E39 in the western coast of Norway, Norwegian Government is planning to build several extreme bridges spanning from 1.5 to 5 km. The region is typically mountainous with deep fjords seeping inland. Here, experience gained from a 5-year monitoring campaign on the Hardanger Bridge in Norway is summarized relating to this ambitious project. The analysis of data provided valuable knowledge on the wind characteristics, which can be generalized for the whole region. Insight has also been gained on the dynamic behaviour of the bridge and how it is influenced by the wind conditions. The results are presented and discussed here with the future bridges in mind.

Keywords: suspension bridge · turbulence characteristics · buffeting response · complex topography · probabilistic modelling

1 Introduction

Structural health monitoring of large or lifeline structures has been extensively carried out in the last two decades. Long-span cable-supported bridges in particular received considerable attention such that almost every major bridge in the world has a monitoring system installed in it. Although the main purpose of such systems are to monitor the structural health and identify any damage or unexpected phenomena, valuable data on environmental conditions and bridge behaviour is collected as a by-product. Such data are commonly used by researchers to improve the state-of-the-art techniques for structural design and assessment such as the wind-resistant design of long-span cable supported bridges.

In 2013, one such project was initiated on the Hardanger Bridge (HB), to this day the longest suspension bridge in Norway, for the sole purpose of research. The data acquired during the monitoring campaign is used to study the wind characteristics and the terrain effects, validity of common assumptions in wind engineering of such structures, performance of buffeting response predictions and also the state-of-the-art design methodology. In this paper, conclusions drawn from the monitoring campaign and their implications on future bridge designs in Norwegian fjords are discussed.

2 Hardanger Bridge Monitoring Project

Hardanger Bridge Monitoring Project (MBMP) has been initiated in 2013 by the Norwegian University of Science and Technology (NTNU) with financial support from the Norwegian Public Roads Administration (NPRA, Statens Vegvesen). It was aimed that the project and the full-scale observations would provide information and insight for the future bridge projects along the E39 Coastal Highway. In particular, the wind characteristics in the fjords, how are they influenced by the particular terrain and in return how they influence the bridge behaviour, were questions of interest.

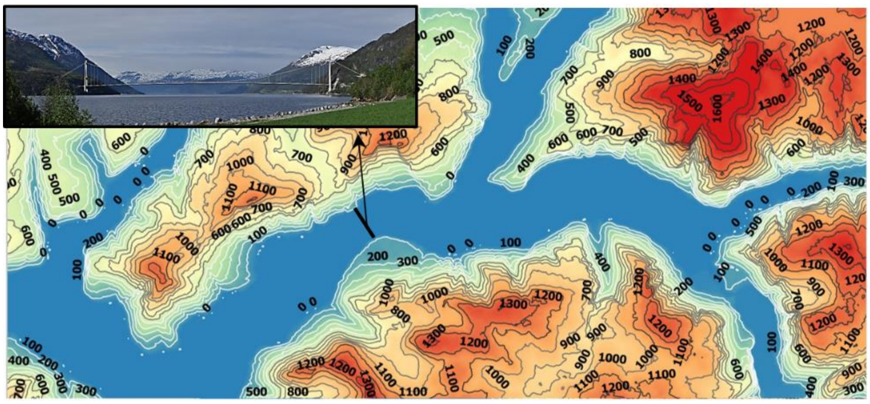

Fig. 1 The Hardanger Bridge and its surroundings

The Hardanger Bridge (Fig. 1) is the longest suspension bridge in Norway as of today with its main span of 1308 meters. The bridge is located in western Norway and it is surrounded by a complex terrain, consisting of steep mountains and fjords in between. Such features makes the HB a very interesting case study, especially when the E39 project is concerned. The bridge was opened for traffic in 2013 and a structural monitoring system was installed on it shortly after. The monitoring system consists of 20 accelerometers, 9 anemometers and several other equipment for data communication and storage. An overview of the monitoring system and sensor locations are presented in Fig. 2 and the pictures of wind and acceleration sensors are shown in Fig. 3. For more information on the monitoring system, the reader is kindly referred to the published papers (Fenerci et al., 2017; Fenerci and Øiseth, 2017).

The monitoring system measures wind velocities and accelerations at the HB site continuously. However, the data is recorded only when a threshold wind speed of 15 m/s (averaged over 1 minute) is exceeded in any of the sensors. In that case, a 30-min recording is taken. The monitoring system has recorded data following such a triggering rule during the 5-year measurement period between 2013 and 2018. Occasionally, the system has also been triggered manually to include the low wind speed data in the database.

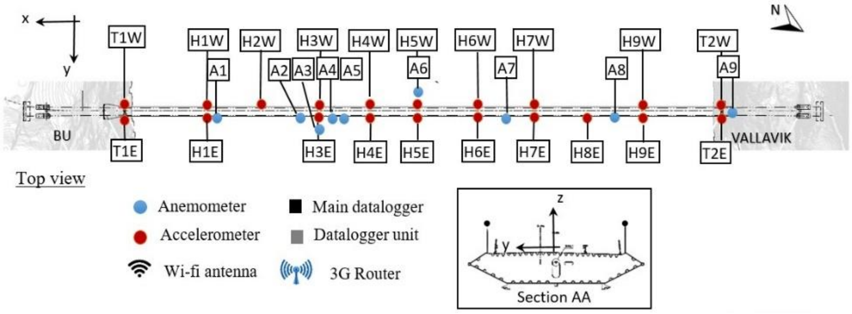

Fig. 3 Sensor layout

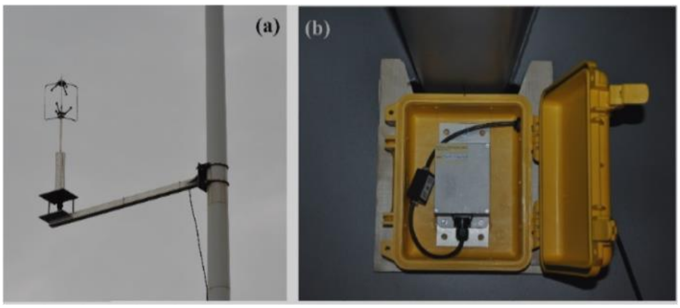

Fig. 4 Sensors: (a) anemometer attached to hanger, (b) accelerometer inside deck

Immediately after a recording is taken at the site, the data is first logged in the main logger unit located at the bridge and then transferred to designated servers at NTNU. A customized computer program then detects the new recording and starts processing data. Initially, the data is filtered, downsampled and transformed to appropriate coordinate systems and adjusted for errors. Both the raw and adjusted data are then stored in a database in the Matlab environment. The organization structure of a single recording in the database is shown in Fig. 5. The data are then processed to extract the interesting statistics concerning wind and response measurements, separately. An averaging interval of 10 minutes, which is rather common in wind engineering, is used to evaluate the statistics of both wind and response. The extracted statistics are then collected in a separate database than the raw and adjusted data. Loading such a database to common scientific computation software such as Matlab or Python, the wind and acceleration statistics for all recordings can be accessed easily. An overview of all 10 minute recordings that has been taken during the monitoring period is given in Fig. 6.

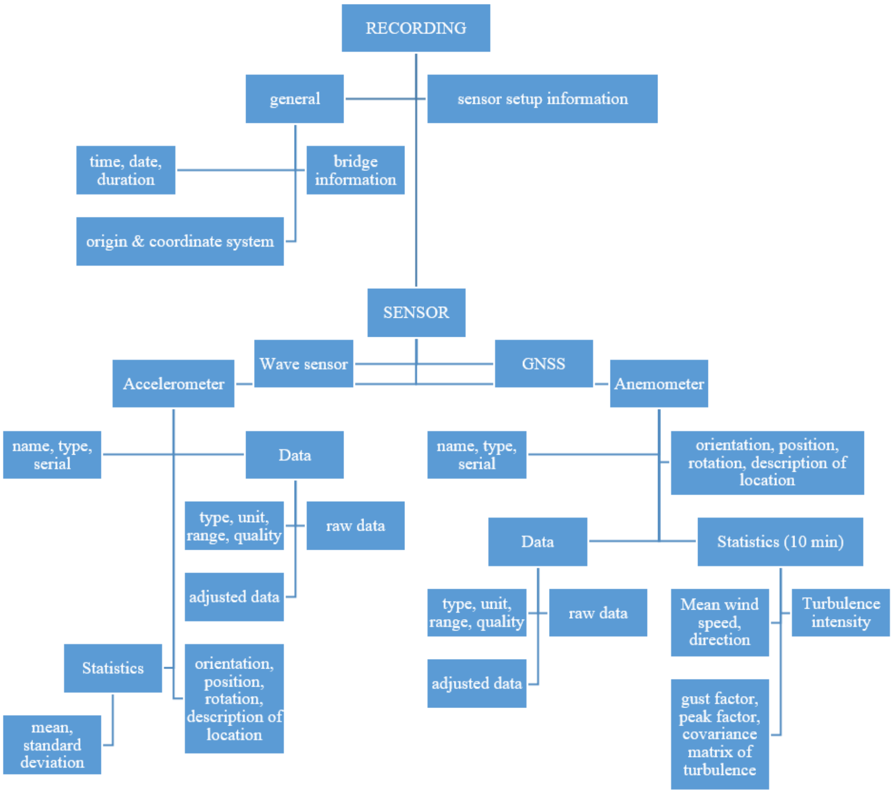

Fig. 5 Organization structure of the database for single recording

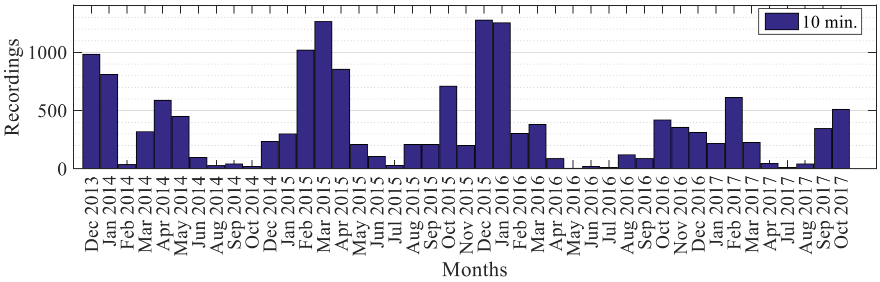

Fig. 6 Overview of 10 minute recordings

3 Randomness in field data & implications on bridge design

Examining the long-term data collected at the HB site, considerable randomness in wind and response characteristics is detected. Detailed analyses of the wind and acceleration data was conducted in Fenerci et al. (2017) and the randomness was attributed to a large extent to the randomness in the wind field. The wind field characteristics were calculated using traditional approaches, assuming stationarity of the time signals during a 10-min averaging interval. The inherent randomness in the resulting wind characteristics was found to be significant even for the high wind speed events, where the wind is fairly stationary and the atmosphere is stable. Such an observation contradicts with the common design practice, where the variable nature of the statistical properties of the turbulence such as turbulence intensities, integral length scales and decay coefficients for spanwise correlation of turbulence components (Davenport, 1961) are overlooked. However, it appears that randomness in such parameters are significant in case of complex terrain and influence the dynamic behaviour to a large extent.

To illustrate how such randomness would affect the design of long-span suspension bridges, analytical predictions of the dynamic response of the HB deck is carried out. The dynamic response of the deck is calculated using fully coupled multimode approach in frequency domain (Chen et al., 2001; Fenerci and Øiseth, 2017; Jain et al., 1996). A time-domain approach is also possible, but nonlinearities in case of the HB are not profound, allowing a much faster frequency domain analysis. The aerodynamic properties of the deck was obtained through forced vibration tests in the wind tunnel by Siedziako et al. (2017) and directly incorporated into the analysis, where the modal properties of the bridge were obtained through finite element (FE) analysis. The static force coefficients of the section are given in Table 1, where the natural frequencies of the bridge are given in Table 2. More detailed information concerning the bridge and the details of the analytical approach can be found in Fenerci and Øiseth (2017).

Table 1 Vibration modes of the Hardanger Bridge

Lateral		Vertical		Torsional	
mode no	freq. (Hz)	mode no	freq. (Hz)	mode no	freq. (Hz)
1	0.05	3	0.11	15	0.36
2	0.098	4	0.14	26	0.52
5	0.169	6	0.197		
10	0.233	7	0.21		

Table 2 Steady-state force coefficients of the Hardanger Bridge deck

$\bar{C}_D$	C'_D	$\bar{C}_L$	C'_L	$\bar{C}_M$	C'_M
1.05	0	-0.363	1.789	-0.017	0.654

* D = drag, L = lift, M = moment (bar denotes mean value and apostrophe denotes derivative)

Buffeting loads on a line-line structure such as the HB deck is commonly represented in frequency domain with the help of a cross-power-spectral-density (CPSD) matrix. In design of long-span suspension bridges; however, turbulence characteristics that defines the CPSD matrix of turbulence are treated as deterministic parameters. The parameters that define the spectra can be estimated using mast measurements at the site, wind tunnel terrain model tests, computational fluid dynamics (CFD) tools combined with mesoscale atmospheric models or on-site measurements or directly using code recommendations. In any case, the parameters would be average values and will result into a deterministic spectra, neglecting the inherent randomness of the turbulence field described earlier. Following such an approach, the turbulence field is modelled with the following formulae:

$$\frac{S_{u,w} f}{\sigma_{u,w}{}^{2}} = \frac{A_{u,w} f_z}{(1+1.5A_{u,w} f_z)^{5/3}}, \quad f_z = \frac{fz}{U}, \quad C_{uu,ww} = \exp(-K_{u,w} \frac{f \Delta x}{U}) \tag{1}$$

where $\sigma_{u,w}$ are the standard deviations of the along-wind (u) and vertical (w) turbulence components. $A_{u,w}$ are the parameters to be fitted. In the expression, $S_{u,w}$ denote the auto-spectral densities, f denotes frequency in Hz and z denotes the height above ground (68 m for the midspan) and U denotes the mean wind velocity. $C_{uu,ww}$ denote the normalized cross spectra of turbulence at two points separated by Δx and $K_{u,w}$ are commonly referred to as decay coefficients, which are also needed to be fitted to data. Therefore, for an estimation of the CSPD matrix of turbulence in modeling of the buffeting actions on the HB, the parameters $\sigma_{u,w}$, $A_{u,w}$ and $K_{u,w}$ need to be estimated from the available data. Here, most probable values (modes) of each parameters were used to model the turbulence field. The modes of each parameter were obtained by fitting lognormal distributions to the field data. Using, such input for the buffeting analysis, the resulting comparison of the measured and analytical dynamic response if given in Fig. 7. The figure shows that the analytical predictions lie somewhere around in the middle of the scatter of the measured response for all of the response components (lateral, vertical and torsional acceleration responses). Clearly, the design curves obtained in such a way will be exceeded by many measurement points since the randomness in the wind field is neglected. Thus, such an observation points out the need for a probabilistic description of the above mentioned turbulence spectra, and a coherent approach for evaluating the corresponding dynamic response.

4 Probabilistic modelling of the wind & turbulence field

Previous investigations showed that the turbulence field at the HB site can be modelled with reasonable accuracy using relatively simple expressions for the CPSD matrix with inclusion of only six turbulence-related parameters. These are namely the turbulence standard deviations ($\sigma_{u,w}$) which give the power of the turbulence components, spectral parameters ($A_{u,w}$) that relate to the spectral content of turbulence and decay coefficients ($K_{u,w}$) which represent the spanwise correlation information of turbulence. The information regarding these parameters gives the full turbulence field along the bridge deck. It should be noted that if the buffeting loading on other components of the structure, such as bridge cables or pylons are going to be considered, more parameters are needed.

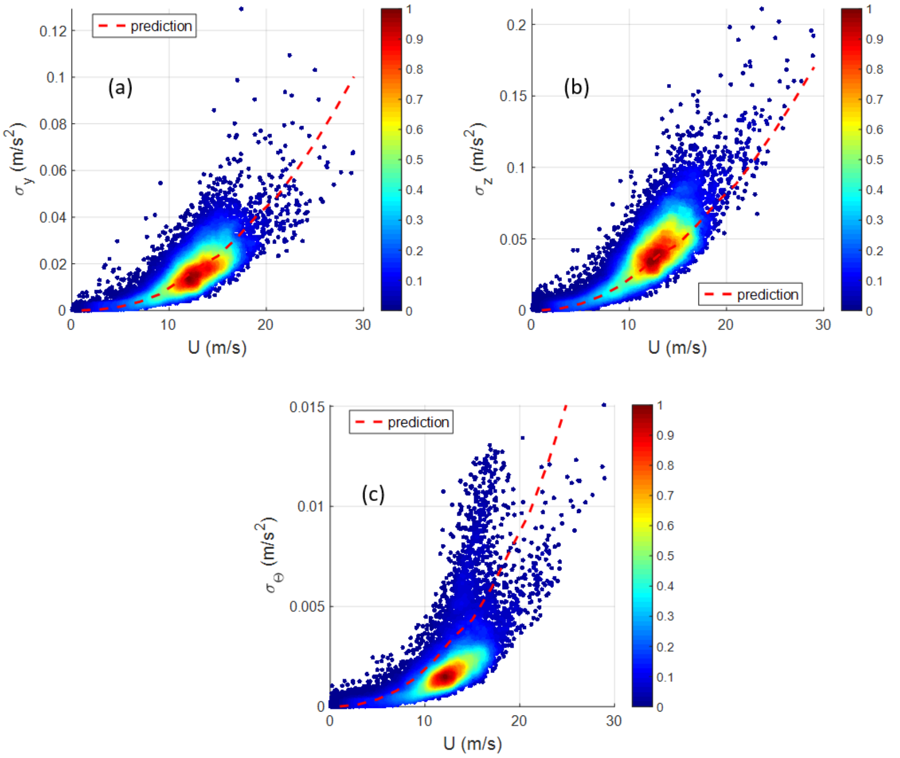

Fig. 7 RMS response at the midspan: (a) lateral (b) vertical and (c) torsional acceleration response

It was observed that all of these parameters accommodate inherent randomness, which can be modeled reasonably well using lognormal probability distributions. Considering the nature of the problem and observing the long-term data, it is also expected that these parameters also depend on the mean wind speed and direction during the averaging period considered. Moreover, the correlation of different parameters can also be significant, for example in the case of parameters for different turbulence components. Therefore, a probabilistic description of the turbulence field along the whole structure requires definition of six lognormally distributed correlated random variables that are conditional on wind speed and direction. This is achieved by dividing the data into two wind directions (easterly and westerly winds) and several wind velocity intervals. The data is then fitted with lognormal distributions and the correlation coefficient matrix of all parameters are calculated. The resulting statistical properties of the six parameters are given in Table 3.

Table 3 Statistical properties of the turbulence parameters

	East			West		
	$\tilde{\mu}$	$\tilde{\sigma}$	ρ	$\tilde{\mu}$	$\tilde{\sigma}$	ρ
σ_u	0.122+0.039U	0.28	0.754	0.122+0.039U	0.28	0.772
σ_w	-0.657+0.032U	0.278		-0.657+0.032U	0.278	
A_u	2.67+0.0248U	0.456	0.15	2.407+0.048U	0.556	0.327
A_w	0.725	0.456		1.247	0.556	
K_u	1.938	0.275	0.267	2.11	0.275	0.459
K_w	1.833	0.415		2.213	0.415	

After establishing the statistical properties of the turbulence parameters, one can simulate many wind fields using Monte Carlo simulations to represent the randomness in the wind field, which was observed in measurements. As an illustrative example, 10 simulations of the one-point spectra and the normalized cross spectra were made for the design wind speed of HB (U = 39 m/s, 50 year return period) in such way using random number generators. The resulting spectra are shown in Fig. 8 for the easterly winds and Fig. 9 for the westerly winds. The difference in the turbulence fields between the two wind directions is also noteworthy and implies the importance of the incoming wind direction on the turbulence structure in case of such complex terrain. Such a probabilistic model is useful especially when a frequency domain approach is adopted. That way, many simulations of the wind field and the analytical response is possible to carry out avoiding exhaustive computation.

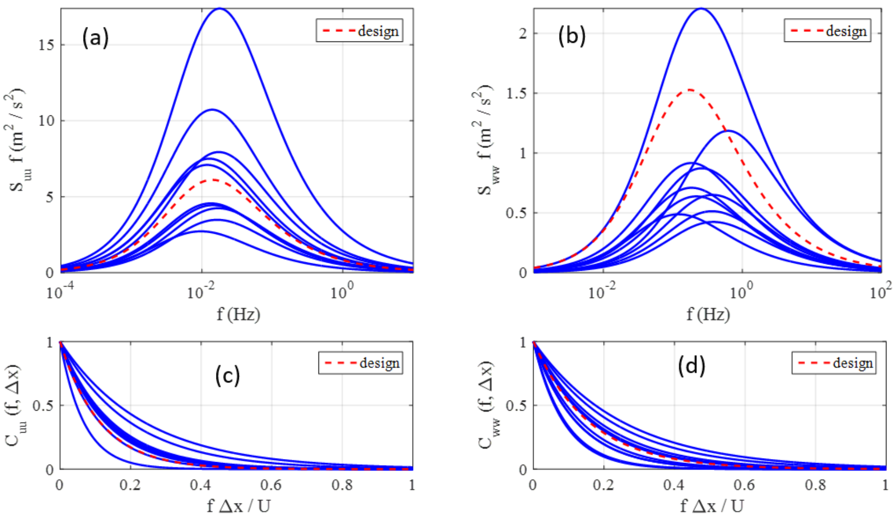

Fig. 8 Simulations of turbulence field for easterly winds under design wind speed (a) One-point spectra of along-wind and (b) vertical turbulence, (c) Normalized cross-spectra for the along-wind and (d) vertical turbulence

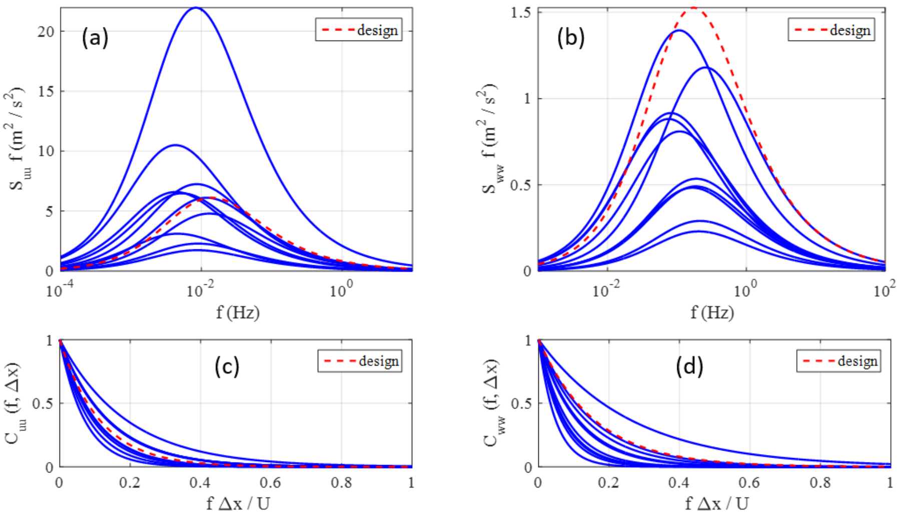

Fig. 9 Simulations of turbulence field for westerly winds under design wind speed (a) One-point spectra of along-wind and (b) vertical turbulence, (c) Normalized cross-spectra for the along-wind and (d) vertical turbulence

5 Insights, challenges and prospects

Traditional structural design against buffeting actions requires prediction of the buffeting response for the design wind speed, where other turbulence parameters such as the turbulence intensity, length scale and coherence of turbulence are modelled deterministically. On the contrary, a look of the data from the HB showed significant variability of the turbulence parameters, which was also reflected into the dynamic response of the bridge (Fenerci and Øiseth, 2017). Therefore, it is suggested that the turbulence field along the bridge is modelled probabilistically, taking into account the variations in turbulence parameters.

The data from the HB were also used to evaluate the analytical predictions using state-of-the-art methods. For such applications, the wind field was modelled with maximum possible accuracy using the on-bridge measurements. Despite this, significant discrepancy was found between measured and predicted responses. Identifying the sources of such discrepancies and improving the predictions poses a great challenge and more research is needed on this topic, exploiting the vast amount of data available.

The wind measurements also showed nonstationary and span-wise non-uniform features (Fenerci and Øiseth, 2018). Although they seem to be of secondary importance, possibility of inclusion of such effects into the design should be investigated. Moreover, when the bridge is not in place such as in the design process, the transfer of full probability distributions of turbulence characteristics from measurement locations to the bridge location should be handled with care (Lystad et al., 2017).

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